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IMPROVED MATERIALS AND MANUFACTURING METHODS FOR GUN BARRELS. PART II

A. L. Hoffmanner, et al

TRW, Incorporated

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IMPROVED MATERIALS AND MANUFACTURING METHODS FOR GUN BARRELS (PART II)

September 1972

TECHNICAL REPORT

Dr. A. L. Hoffmanner TRW, Inc.
and
J. D. DiBenedetto , Dr. K. R. Iyer
USAWECOM

RESEARCH DIRECTORATE

WEAPONS LABORATORY USAWECOM

RESEARCH, DEVELOPMENT AND ENGINEERING DIRECTORATE

U. S. ARMY WEAPONS COMMAND

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13. ABSTRACT

New and efficient metal-shaping procedures for the fabrication of 7.62mm gun barrels were evaluated under the direction of the Research Directorate, Weapons Laboratory USAWECOM. The materials considered were Inconel 718, Vasco-Jet M-A (CVM), and a cobalt-base alloy in powder form. Gun drilling, ECM stem drilling, hot piercing and extrusion, and filled-billet extrusion were evaluated for tube fabrication before subsequent precision rotary swaging of the rifling. Gun drilling of these alloys was the most economical tube fabrication procedure. The filled-billet technique is most amenable to consolidation-tube fabrication from powdered alloys. Precision rotary-swaging was evaluated for rifling the tubes and for determining the feasibility of combined rifling and chambering during swaging. Precision of the bore dimensions was maintained to less than $\pm$ 0.00005 inch. Tube preparation was not a significant problem. The feasibility of swaging simultaneously the chamber and rifling was demonstrated for Inconel 718 and for Vasco M-A at hardness below R_c 36. The cobalt base alloy could not be swaged. ECM chambering was developed by production of chambers with accurate dimensions and with surface finishes below 20 microinch. The total operational sequence for barrel fabrication from superalloy was evaluated and optimum approaches defined based on the results of this program. (U) (Hoffmanner, A. L., DiBenedetto, J. D. and Iyer, K. R.)

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Details of Illustrations in this document may be better studied on microfiche

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ABSTRACT

New and efficient metal-shaping procedures for the fabrication of 7.62mm gun barrels were evaluated under the direction of the Research Directorate, Weapons Laboratory USAWECOM. The materials considered were Inconel 718, Vasco-Jet M-A(CVM), and a cobalt-base alloy in powder form. Gun drilling, ECM stem drilling, hot piercing and extrusion, and filled-billet extrusion were evaluated for tube fabrication before subsequent precision rotary swaging of the rifling. Gun drilling of these alloys was the most economical tube fabrication procedure. The filled-billet technique is most amenable to consolidation-tube fabrication from powdered alloys.

Precision rotary-swaging was evaluated for rifling the tubes and for determining the feasibility of combined rifling and chambering during swaging. Precision of the bore dimensions was maintained to less than ± 0.00005 inch. Tube preparation was not a significant problem. The feasibility of swaging simultaneously the chamber and rifling was demonstrated for Inconel 718 and for Vasco M-A at hardness below R_c 36. The cobalt base alloy could not be swaged.

ECM chambering was developed and demonstrated by production of chambers with accurate dimensions and with surface finishes below 20 microinch.

The total operational sequence for barrel fabrication from superalloy was evaluated and optimum approaches defined based on the results of this program.

FOREWORD

This report was prepared by Dr. A. L. Hoffmanner, of TRW, Inc., Cleveland, Ohio 44117, in compliance with contract DAAF01-71-C-0410; and by Mr. J. D. DiBenedetto and Dr. K. R. Iyer of the Research Directorate, Weapons Laboratory USAWECOM, U. S. Army Weapons Command.

The work was authorized as part of the Manufacturing Methods and Technology Program of the U. S. Army Materiel Command which is administered by the U. S. Army Production Equipment Agency.

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1.0 INTRODUCTION

The erosive, corrosive, and high-temperature environments produced by rapid firing schedules cannot be withstood by conventional barrel materials. Although several high-temperature alloys are available which might meet the requirements of these environments, these highly alloyed materials are expensive and difficult to fabricate by conventional procedures. Therefore, the objective of this program was to fabricate gun barrels (Rock Island Drawing F11701204, Figure 1) from improved materials of high potential for resistance to environments of rapid firing schedules by use of efficient shaping processes. The following three alloys were chosen by the Research Directorate, Weapons Laboratory USAWECOM, on the basis that could provide a significant demonstration of advanced barrel fabrication procedures:

1. Nickel - chromium alloy Inconel 718;
2. Matrix steel Vasco M-A (CVM);
3. Cobalt-base alloy 31.9%Fe, 12.8%W, 0.5%C, Bal. Co, produced from the alloy powder.

Each of the selected alloys had unique properties that indicated individual fabrication sequences to achieve economy during processing and the desired mechanical properties in the product for successful performance. The general approach which has followed included "tailoring" each processing sequence for the specific alloy by use of conventional and advanced gun tube fabrication techniques combined with rotary swaging with the material condition being a controlled variable in each step of the process. With this approach, in which the effect of material and condition was considered, the resulting use of each processing step was determined. The overall results are provided in terms of tool life, machining time, and quality data summarized by an economic evaluation of each processing step and of the overall sequence.

The selection of a specific manufacturing process from scaled or pilot fabrication processes requires that precise economic evaluations be obtained for testing the many alternatives by which the manufacturing process could be followed. These considerations should include the following:

1. Material (the specific alloy) and material costs;
2. Material condition;
3. Capital investment for machinery which affects overhead rate;
4. Machine cycling rate and number of pieces per machine cycle;

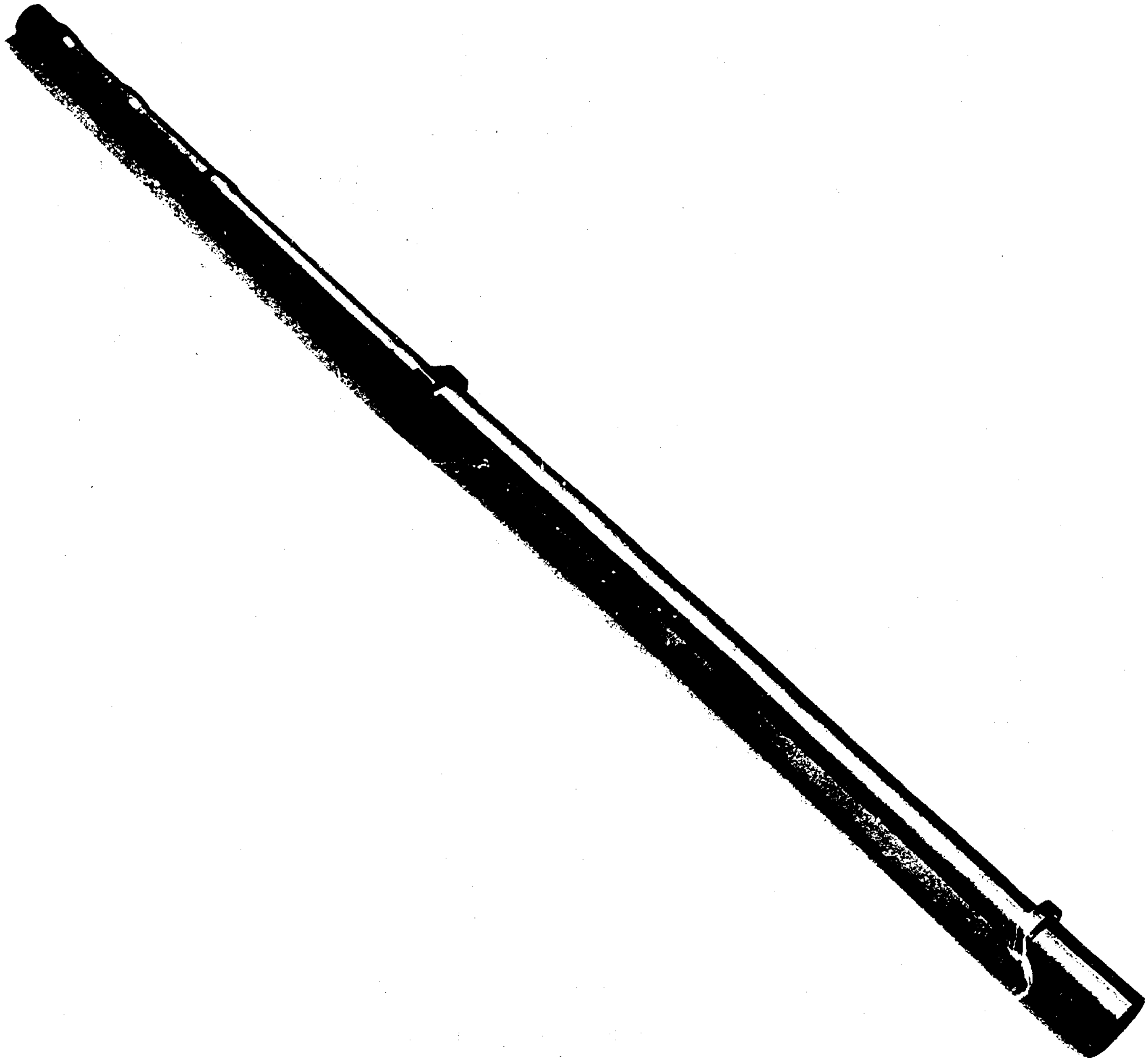


Figure 1. Minigun Barrel (U.S. Army, Rock Island Drawing No. 11701204).

5. Machine tool costs and regrind costs;

6. Setup, tool change, and recharge time;

7. Machine maintenance costs;

8. Conditions set on the final product, i.e., size, tolerances, surface quality and finish, and strength or hardness.

The alternatives to which these considerations would be applied are described in Figure 2 constructed for producing swaged barrels from solid bar stock. The broken lines shown on this figure for distinguishing single from multiple blank production are based on blank length and the number of multiples of the blank length utilized in the process. For example, both ECM and deep hole or gun drilling are single blank processes from the starting bar stock, whereas cored extrusion and pierced and extruded blanks could be produced from larger diameter bar stock to produce multiple blanks or tubes. However, the hot piercing and extrusion process is not well suited for very long lengths of thick wall tubes because of the required mandrel length resulting in significant drag and wear of the mandrel. The cored or filled billet extrusion process is not limited by these problems, but concentricity of better than $\pm$0.005 inch is difficult to obtain with this technique. Therefore, the factors involved in the competition between piercing and extrusion and cored extrusion are mandrel costs, core removal and dimensional control. All of these factors must be evaluated on the basis of cost per blank. The cored billet approach is most amenable to processing from the powdered alloy, and, therefore, the economics would change depending on whether solid bar or prealloyed powder were used as the starting stock.

The procedures which appeared to have the greatest potentials for success with the selected alloys included extrusion of filled billets (Co-base alloy), hot piercing and extrusion for Inco 718, ECM drilling for Inco 718 and hardened Vasco MA and gun drilling for Inco 718 and Vasco MA at hardness levels below about R_c40. Although gun drilling, per se, cannot be viewed as an advanced method in barrel manufacture, there are severe problems in gun drilling superalloys and high strength steels arising from poor tool life due to minor variations in alloy chemistry and hardness. If gun drilling can be performed without tool replacement for a hole length in excess of the barrel length, this procedure would be one of the most economical for barrel preparation.

Intermediate and final heat treatments were utilized to determine the feasibility of preparing the blanks for subsequent processing and to avert dimensional changes produced by heat treatments after processing. The exact position of a particular heat treatment in the processing sequence had a profound effect on processing costs and, therefore, the feasibility of the processing sequence. The compromises which were faced in selecting the optimum sequence included production rate, secondary conditioning treatments, and the

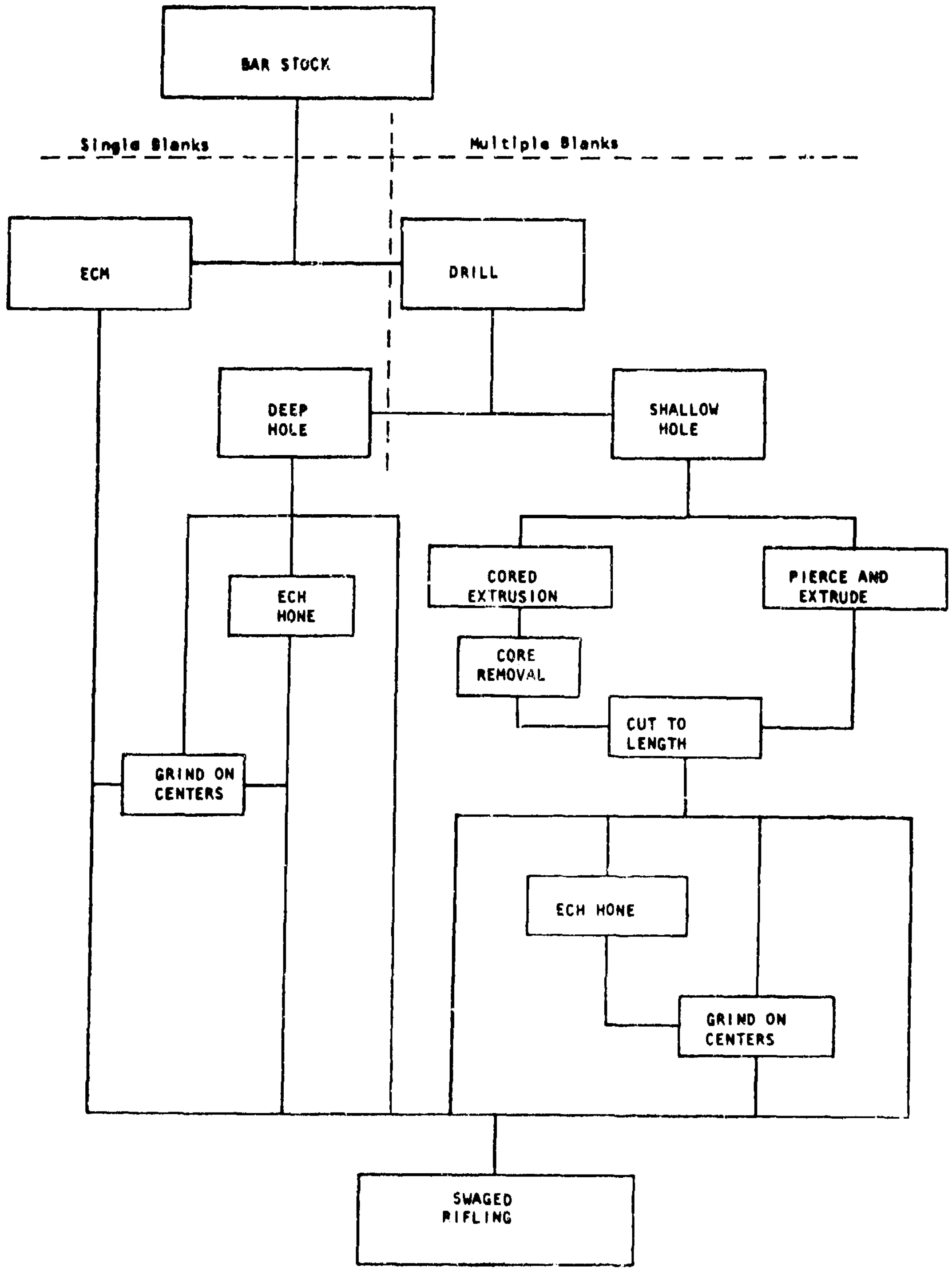


Figure 2. Potential processing sequences for fabrication of tubes for subsequent processing into rifle barrels.

possibility that heat treatments to aid fabricability and processing economy could permanently affect the performance potential of the finished barrels. Decisions on compromises were complicated by the fact that the levels of erosion-corrosion resistance, fracture toughness or impact strength, high temperature strength, etc. required for optimum performance during rapid firing schedules are not known. Therefore, there was no exact basis for defining a thermal-mechanical sequence or heat treatments for producing barrels from these alloys. For these reasons, barrels of each alloy were made with at least two distinct levels of mechanical properties produced by heat treatments and mechanical working. Within each property level, heat treatments and fabrication schedules were alternated and modified to determine cost and quality of barrels produced from the various sequences.

2.0 SUMMARY OF PROGRAM RESULTS

The following is a brief summary of the more significant developments and observations resulting from this program effort. A detailed description of the total program effort and results is presented in the following section on results.

The results obtained for gun drilling were encouraging because, in general, actual performance was found to exceed the anticipated based on handbook and state-of-the-art data. The gun drilling results for Inconel 718 and Vasco M-A in terms of barrel length drilled for 0.010 inch maximum wear land can be summarized as follows:

Material	Hardness (R_c)	Speed (SFM*)	Feed (in./min.)	Tool Life (in.)
Inconel 718	22 $\pm$ 2	100	0.4	25
Inconel 718	22 $\pm$ 2	50	0.3	100
Inconel 718	36 $\pm$ 1	100	0.6	25
Inconel 718	45 $\pm$ 1	50	0.3	25
Inconel 718	45 $\pm$ 1	100	0.6	2
Vasco M-A	36 $\pm$ 1	200	1.8	125+
Vasco M-A	55 $\pm$ 1	50	0.3	1

* Surface feet per min.

Although this performance was achieved with a special tool geometry, the special drill and bit are comparable in cost and maintenance to a conventional gun drill. It will be shown that gun drilling is the most economical procedure for tube fabrication for these two alloys.

ECM stem drilling of both Inco 718 and Vasco M-A was investigated. A feed of approximately 0.030 inch/minute was established with a hole straightness of 0.0005/inch/inch or better. With improved fixturing and internal electrode guiding, a feed of about 0.060 inch/minute appears attainable with the same straightness. However, even under these improved conditions this process does not appear competitive with gun drilling for Inco 718 and Vasco M-A.

Hot piercing and extrusion of Inco 718 was investigated under a variety of conditions to achieve improved mandrel performance and to determine the minimum hole size capability of this technique. A minimum bore diameter of 0.31 inch was obtained; however, a bore taper 0.075 inch from front-to-back in 24 inches was required to prevent mandrel breakage. It is doubtful the smaller diameters in Inco 718 can be achieved by this technique. Quality requirements on structure and surface finish of the bore would definitely necessitate subsequent bore finishing with a minimum of 0.004 inch of stock removed from the inner diameter, although the bore quality was considered very good for a hot extruded product. The major problem with this technique is straightness. Special straightening equipment would be required for production application of this procedure.

The filled billet extrusion of the Co-base alloy powders produced thick walled tube with an eccentricity less than $\pm$ 0.0035 inch. As with hot piercing and extrusion, straightness was a problem in producing barrel blanks with this procedure. Electron microprobe analysis of these tubes indicated that carbon loss at the bore had occurred to a depth of about 0.005 inch. Therefore, the bores of these blanks were finished prior to swaging.

Precision rotary swaging was performed on a Cincinnati Milacron Intraform with blanks of all three alloys in various conditions of heat treatment and dimensional quality as determined by the total indicated runout of the inner and outer diameter. In general, swaging improved the dimensional precision of the gun tubes and produced a bore finish of approximately 18 microinch AA* independent of the finish on the starting blank. Swaging trials on half-length tube segments demonstrated that gross reductions required for complete simultaneous rifling and chambering by swaging can be achieved with Inco 718 and Vasco M-A at hardness levels below Rockwell C36. The dimensional precision along the bore surface was found to be on the order of 0.0001 inch.

* Arithmatic average

Barrel finishing was performed in a conventional manner using rough turning on a tracer lathe, O.D. form grinding and chamber reaming and polishing. Because of the small lot size these techniques were performed in a tool room, although they were scheduled and routed similar to a production operation to provide a basis for evaluating production cost relative to Cr-Mo-V barrels. A new procedure for chambering was developed which involved chamber finishing and polishing combined in one electrochemical machining (ECM) operation. Stock removal over the chamber form was achieved at rates of 0.0005 to 0.0010 inch/sec. with surface finishes as low as 20 microinch AA. This technique is readily adaptable to automated production. This ECM chamber finishing technique is very useful for high strength and heat resistant barrel materials because these materials produce poor tool life during conventional machining.

3.0 RESULTS

The presentation of results will follow the processing scheme described in Figure 1. Rather than discuss each material separately, the steps used for barrel fabrication will be described in sequence with the data for each alloy.

3.1 Material

The alloy stock was selected in various conditions to provide the following:

1. Economy by being in a readily obtainable form suitable for subsequent fabrication,
2. Quality for barrel performance by having a suitable microstructure, and
3. Fabrication flexibility by being in a form amenable to subsequent processing and alternatives to clearly demonstrate the objectives of the program.

The initial conditions of the alloy stock are listed in Table 1 which includes the material and composition, stock size, initial heat treatment, the heat treating atmospheres, and total indicator reading for runout before and after heat treatments, but prior to tube fabrication. The runout documented in this report was determined by the maximum indicator displacement observed during rotation of the blank or barrel on two pairs of precision balancing wheels spaced 10 inches apart. The center of the blank or barrel was located midway between the wheels and measurements were taken at each end and in the middle of each bar. Additional measurements were made at the inner diameters of the tubes to determine runout of the bore. Unless otherwise specified, runout measurements correspond to determinations using these procedures. Maximum runout of 0.0005 inch/inch was initially considered tolerable for subsequent gun drilling and swaging. However, this condition was subsequently relaxed with no adverse consequences. This finding probably results from the fact

TABLE I

Initial Material Condition

Inconel 718: 1.265 ± 0.002 inch diameter x 23 inch long centerless ground bar stock, heat treated according to AMS specification 5662 (R_c 35/37). Grain Size - ASTM12-12.5 certified

(For subsequent gun drilling and ECM stem drilling)

Bar No.	Initial Max. Runout (in.)	Heat Treatment Prior to Tube Fabrication	Hardness After Heat Treatment R_c	Max. Runout After Heat Treatment (in.)
1-1	0.012	AMS5662	36±1.0	0.012
1-2	0.009	IV*	33.6±0.3	0.008
1-3	0.012	IV	33.6±0.3	0.011
1-4	0.011	IV	33.6±0.3	0.011
1-5	0.005	AI*	22±1.0	0.008
1-6	0.002	IIV*	41±0.2	0.004
1-7	0.005	AI	22±1.0	0.007
1-8	0.009	AMS5662	36±1.0	0.009
1-9	0.008	AMS5662	36±1.0	0.008
1-10	0.007	AMS5662	36±1.0	0.007
1-11	0.013	AMS5662	36±1.0	0.013
1-12	0.007	AMS5662	36±1.0	0.007
1-13	0.004	AMS5662	36±1.0	0.004
1-14	0.002	AMS5662	36±1.0	0.002
1-15	0.002	I*	45±0.8	0.010
1-16	0.002	I	45±0.8	0.008
1-17	0.003	I	45±0.8	0.009
1-18	0.006	I	45±0.8	0.006

Inconel 718: 3.056 inch diameter x 5.10 long centerless ground billets, heat treated according to AMS specification 5662 (R_c 35/37). Purchased as one 63 inch length of centerless ground bar. Grain size - ASTM 12-12.5 certified.

(For subsequent hot piercing and extrusion)

Billet No.	Heat Treating Prior to Tube Fabrication	Hardness R_c	Maximum Runout (in.)
S1 through S8	AI	22±1.0	0.005
H9 through H12	AMS5662	36±1.0	0.005

TABLE I (Continued)

* Inconel 718 Heat Treatments:

IV: Vacuum anneal 1 hour at 1750°F $\pm$ 25°F followed by N_2 purge quench to below 800°F and air cool.

AI: Neutral salt bath anneal 1 hour at 1750°F $\pm$ 25°F followed by very rapid forced air cool to below 800°F.

IIV: Vacuum anneal 1 hour at 1900°F followed by N_2 purge quench to below 800°F, age in vacuum at 1400°F for 10 hours, furnace cool (100°F/hour maximum cooling rate) to 1200°F, hold for a total of 20 hours and air cool.

I: Age in air at 1325°F $\pm$ 15°F for 8 hours, furnace cool (100°F/hour maximum cooling rate) to 1150°F, hold for a total of 18 hours and air cool.

Vasco M-A, 1.250 inch diameter x 23 inch long centerless ground bar stock in the as-hot worked condition R_B94/96. Grain size - Measured: extremely fine and difficult to detect, less than ASTM12.

Bar No.	Initial Max. Runout (in.)	Heat Treatment Prior to Drilling	Hardness After Heat Treatment R_c	Maximum Runout After Heat Treatment (in.)
M-1	0.013	none	-	-
M-2	0.008	HT1*	55$\pm$1	0.004
M-3	0.010	HT1	55$\pm$1	0.025
M-4	0.010	HT2*	37$\pm$1	0.023
M-5	0.009	HT2	37$\pm$1	0.015
M-6	0.007	HT2	37$\pm$1	0.017
M-7	0.008	HT2	37$\pm$1	0.018
M-8	0.009	HT2	37$\pm$1	0.024
M-9	0.008	HT2	37$\pm$1	0.016
M-10	0.007	HT2	37$\pm$1	0.015
M-11	0.013	HT2	37$\pm$1	0.019
M-12	0.007	HT2	37$\pm$1	0.021

TABLE I (Continued)

* Heat Treatments:

1. Austentize (HT1 and HT2 are tempers after the following austenitizing treatment:

   a) Preheat - 1500°F for 1/2 hr. in neutral salt bath,

   b) High heat - 2025°F ± 25°F for 15 minutes in neutral salt bath, and

   c) Quench in neutral salt at 1050°F and air cool to below 150°F.

2. Triple Temper:

   a) HT1 - triple temper: 1100°F ± 10°F in neutral salt for 2 hours + air cool to below 150°F after each temper.

   b) HT2 - triple temper: 1250°F ± 10°F in neutral salt for 2 hours + air cool to below 150°F after each temper.

Cobalt base alloy: 130 pounds -60 mesh powder
5 pounds -20 mesh powder

Analyzed chemical composition (in weight percent):
54.12 Co
32.27 Fe
13.10 W
0.54 C
Less than 80ppm O

that gun drilling produces a very straight hole and although the hole may depart from the centerline due to bow of the blank, swaging straightens the blank and maintains a straight hole. Although the coincidence of the hole with the centerline was improved, the swaging reduction was not sufficient to achieve complete coincidence.

The results in Table I show that the effects of heat treatment on runout of Inco 718 is very small. This observation is in contrast with the results on Vasco M-A where the average maximum runout increased by a factor of 2 to 3. This behavior was anticipated because of the comparatively very low strength of steel at the usual austenitizing temperatures. In order to reduce this distortion, the blanks were hung vertically in a neutral salt bath from a wire through a diametral hole in one end of each blank. Although this procedure is known to reduce distortion, the amount which occurred was considered to be unavoidable. No special precautions were used for Inco 718.

The material conditions selected for barrel fabrication were based on handbook data, but are empirical from the standpoint that these conditions are anticipated to provide good barrel performance and process demonstration. However, in both cases, relatively little is known. The objective of using both hardened and annealed blanks is to demonstrate process feasibility with and without high temperature heat treatments after swaging. However, both solutioning and aging treatments after swaging of Inco 718 are not anticipated to produce any significant problems for chromium plated barrels. These treatments on steels would be expensive because of straightening.

Micrographs from longitudinal sections of Inco 718 and Vasco M-A are shown in Figures 3 and 4 for the soft and hardened conditions. The soft condition for Inco 718 was obtained with the 1 hour anneal at 1750°F followed by a very rapid air cool and the hardened condition is as received or AMS5662. For Vasco M-A, the soft condition is as hot worked or as received and the hardened condition was obtained by austenizing and triple tempering at 1250°F. Longitudinal sections are shown because they demonstrate more clearly the mechanical texturing of grains, carbide and second phase particles. In general, the transverse sections exhibit equiaxed grains with an apparent fine, random distribution of second phase particles.

3.20 Tube Fabrication

Tube fabrication was performed by gun drilling, ECM stem drilling, hot piercing and extruding and filled billet extrusion. The results for each tube fabrication will be presented in order with the data obtained for each alloy.

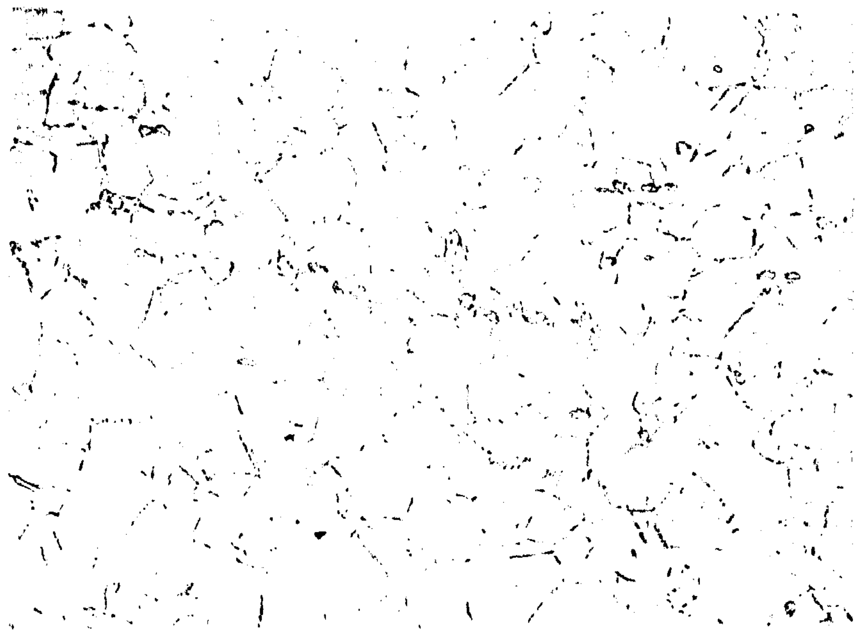


Figure 3a. Longitudinal section of bar I-2 in the as-received (AMS5662) condition. 250X.

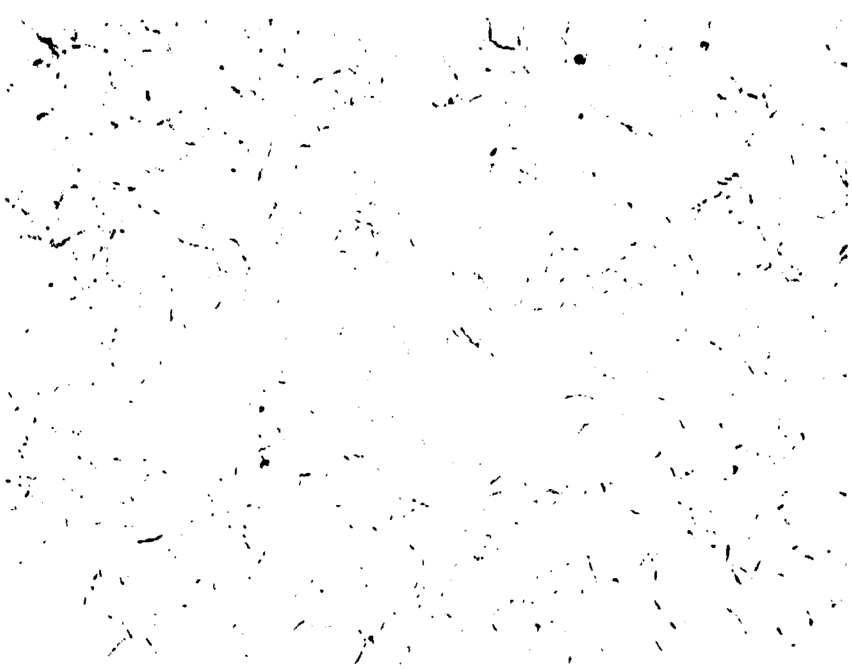


Figure 3b. Longitudinal section of bar I-21 after annealing for 1 hour at 1750°F. 250X.

Figure 3. Photomicrographs of Inco 718 bars in the as-received and annealed conditions.

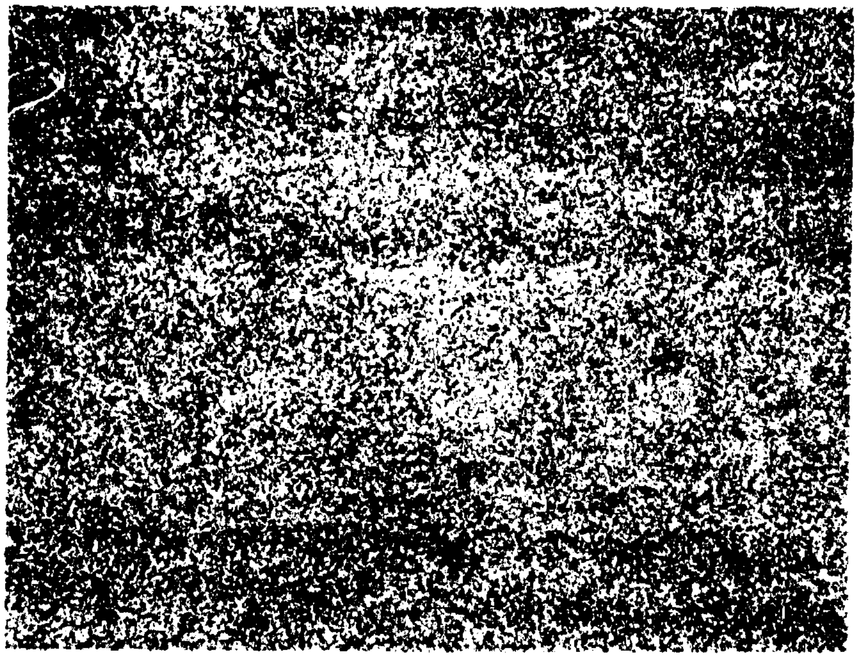


Figure 4a. Longitudinal section of Vasco M-A bar M-2 in the as-received (as hot worked) condition. 250X.

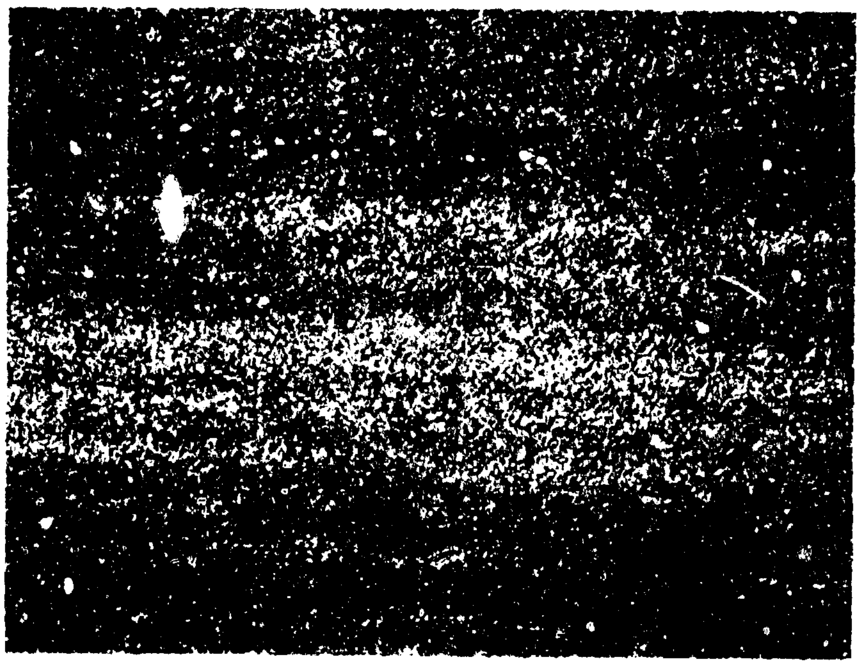


Figure 4b. Longitudinal section of Vasco M-A bar M-4 in the as-heat treated condition (R_c37). 250X.

Figure 4. Longitudinal section of Vasco M-A bars in the as-received and heat treated conditions.

3.21 Gun Drilling

Gun drilling was performed on a Pratt & Whitney Model 1/2B Deep Hole Driller with the following constant drilling parameters:

1. Cutting fluid: Franklin "Peerless" medium heavy weight oil (Control No. 71571) containing 3.3%S, 2.7% Chlorine and 21% fat.

2. Oil pressure: 1000 psi.

3. Gun drill: 36 inch long drill with a Sandvik CA6 modified bit with an Eldorado gun drill N-73E nose grind. The tool bit geometry is shown in Figure 5. Hole diameters of 0.3125, 0.3160, 0.3281 and 0.3937 inch are used.

4. Drill Sharpening: Eldorado Model B Pointer was used for all regrinds. Regrinding was performed dry with a 6 inch diameter diamond face wheel with 1 inch of diamond facing. This wheel was a 180 grit resinoid bonded diamond N grade wheel.

Gun drilling was performed with the tailstock torque control in the completely unloaded position. Because of friction, maximum torque of 25 inch-pounds was required to stop both feed and speed under these conditions. Although some drill breakage was encountered, the torque never became large enough to shut down the machine.

The gun drilling results in Table II show the tool life, runout, surface finish and tool wear surface description for Inco 718 and Vasco M-A for the variety of hardnesses, cutting speeds and tool feeds evaluated. The results for Inco 718 clearly indicate that selection of optimum drilling cannot be simply achieved. Initial trials were performed at relatively low speeds (50 SFM or surface feet per minute) and low feeds (0.11 to 0.17 inch/minute) on material at R_c36 and resulted in poor tool life due to tool breakage and chipping. The small wedge shaped or triangular chips observed under these conditions indicated that in-feed may have been too light and caused tool chatter leading to face chipping. Therefore, the feed was increased, a well curled chip was obtained and tool life became limited by wear rather than chipping. It was also found that high speeds and feeds also produced chipping. Therefore, the region of optimum performance for Inco 718 appeared to be bounded by occurrence of tool breakage and edge chipping.

The speeds and feeds in Table II were established as a factorial design centered about the gun drilling conditions recommended for superalloys and high strength steels in current machinability data handbooks (1). The factorial design is an efficient experimental plan suitable for multivariable linear regression analysis. This analysis was attempted with the data in Table III

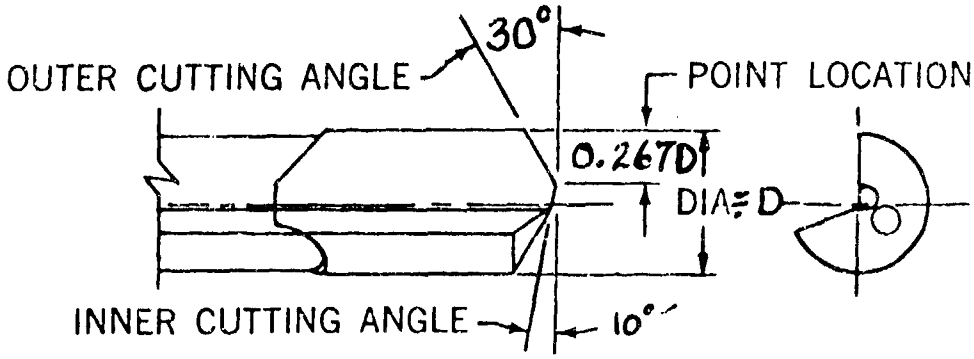


Figure 5. Gun drill bit geometry (Eldorado N73E Grind)

TABLE II

Gun Drilling Results

Specimen No.	Hardness R_c	Speed (ft./min.)	Feed (in./min.)	Tool Life (inch)	Total Indicated Runout (inch) of I.D.	Surface Finish$_6$ (inx10^{-6}AA)	Wear Surface Description	Remarks
I-1	36	50	0.174	12.5*			0.13" face chip	
		50	0.174	6.25*			0.025 " "	
		50	0.290	4.5*	0.003		0.006 " "	
I-4	33.6	100	0.336	12.7**			0.007" wear land	
		100	0.336	10.3**	0.007		0.011 " "	
I-5	22	100	0.224	8.0*			0.03" face chip	cracked bit
		100	0.224	4.0*			0.032 " "	
		100	0.336	11.0	0.004		0.015 " "	
I-7	22	50	0.290	23**	0.004		0.002" wear land	
I-8	36	50	0.290	8				broken bit
I-9	36	100	0.112	8.1*			0.022" face chip	
		100	0.112	14.9*	0.005		0.026" " "	
I-10	36	100	0.224	23*	0.006	65	0.130" " "	
I-11	36	50	0.46	1*			0.060" " "	
		50	0.290	22*	0.005		0.008" wear land	
I-12	36	100	0.56	23*	0.004		0.010" wear land	
I-13	36	100	0.56	23**	0.037		0.010" " "	
I-14	36	100	0.336	23**	0.060		0.009" " "	
I-15	45	100	0.56	**			0.010" " "	
		100	0.56	1**			0.008" " "	
		50	.34	21**	0.017		0.010" " "	
I-16	45	50	.34	23**	0.033		0.008" " "	
I-17	45	50	0.174	23**	0.070		0.008" " "	
I-18	45	50	0.174	23**	0.012		0.006" " "	
M-1	96++	200	1.34	23+	.025	16	0.005" " "	
M-3	55	50	0.29	0.7**	-		0.010" " "	extreme chatter
M-3	37	200	1.8	22+	0.025		negligible	Reheat treated
M-4	37	200	0.90	23+	0.017		negligible	continued
M-5	37	100	1.34	23+	0.022	135	negligible	continued
M-6	37	100	0.90	23+	0.016		>0.004" wear land	Total for M-4,5,6
M-7	37	200	1.34	23+	0.015		negligible	continued
M-8	37	200	1.8	23+	0.015		negligible	continued
M-9	37	150	1.01	23+	0.011		negligible	continued
M-10	37	200	1.34	23+	0.012		negligible	continued
M-11	37	150	1.01	23+	0.016		negligible	continued
M-12	37	200	0.90	23+	0.013	135	0.006" wear land	Total for M-7,8,9,10,11,12

* Tool bit chipping was principal wear mode.

** Edge wear was principal wear mode.

\+ Minimal wear on all pieces.

\++ Rockwell B hardness

TABLE III

Gun Drilling Conditions for Inco 718
Where Tool Life was Determined only by Wear
During Drilling of one 23 inch Long Blank

Hardness (R_c)	Speed (SFM)	Feed (inch/min.)	Wear Land (inch)
22	50	0.29	0.002
36	100	0.56	0.010
36	100	0.56	0.010
36	100	0.34	0.009
36	50	0.29	0.008
45	50	0.34	0.010
45	50	0.34	0.008
45	50	0.17	0.008
45	50	0.17	0.006

for 718, where tool life was only limited by wear, to determine the total tool life dependence on speed, feed and hardnesses within the range of the variables investigated. Such an analysis would permit specification of optimum drilling conditions. A statistically significant Taylor tool life expression (2) in terms of an empirical tool life factor of wear land length per unit length of hole, speed, feed and hardness could not be determined apparently due to the lack of sufficient data and the complex dependence of tool bit chipping on drilling conditions and hardness. Therefore, the optimum drilling conditions can only be surmised from the results in Table III. These drilling conditions for a minimum tool life of 23 inches per sharpening are as follows:

	Hardness	Feed	Speed
Inco 718	22-36	0.6in/min	100 SFM
	45	0.34in/min	50 SFM
Vasco M-A	(tool life of approximately 200 inches)		
	36	1.8	200 SFM

The results for Vasco M-A approximate gun drilling practice for Cr-Mo-V steels at the same hardness.

The results in Table II for total indicated runout (T.I.R.) of the inner diameter from center show large values for I-12, I-13, I-16 and I-17 which are not characteristic of good gun drilling practice. This lack of concentricity of I.D. and O.D. was intentional to test for the necessity of holding close tolerances during manufacturing. The effects of this condition on barrel quality will be discussed in the section on swaging.

Figures 6 and 7 are profilometer traces for blanks I-10 and M-1 respectively which show mechanical surface quality in terms of surface finish, roughness and waviness. It will be shown that the surface finish of the blank bears no resemblance to the finish of the swage barrel.

The complete cycle time of the gun drilling operation was determined by the blank length and feed rate (the working sequence), discharging and charging of a new blank. The working sequence can be calculated from the recommended feed rates and both charging and discharging times took about 1 minute each for the drilling machine which was used. Resharpening and inspection of a worn gun drill required approximately 3 minutes and replacement of the drill in the machine required approximately one-half minute.

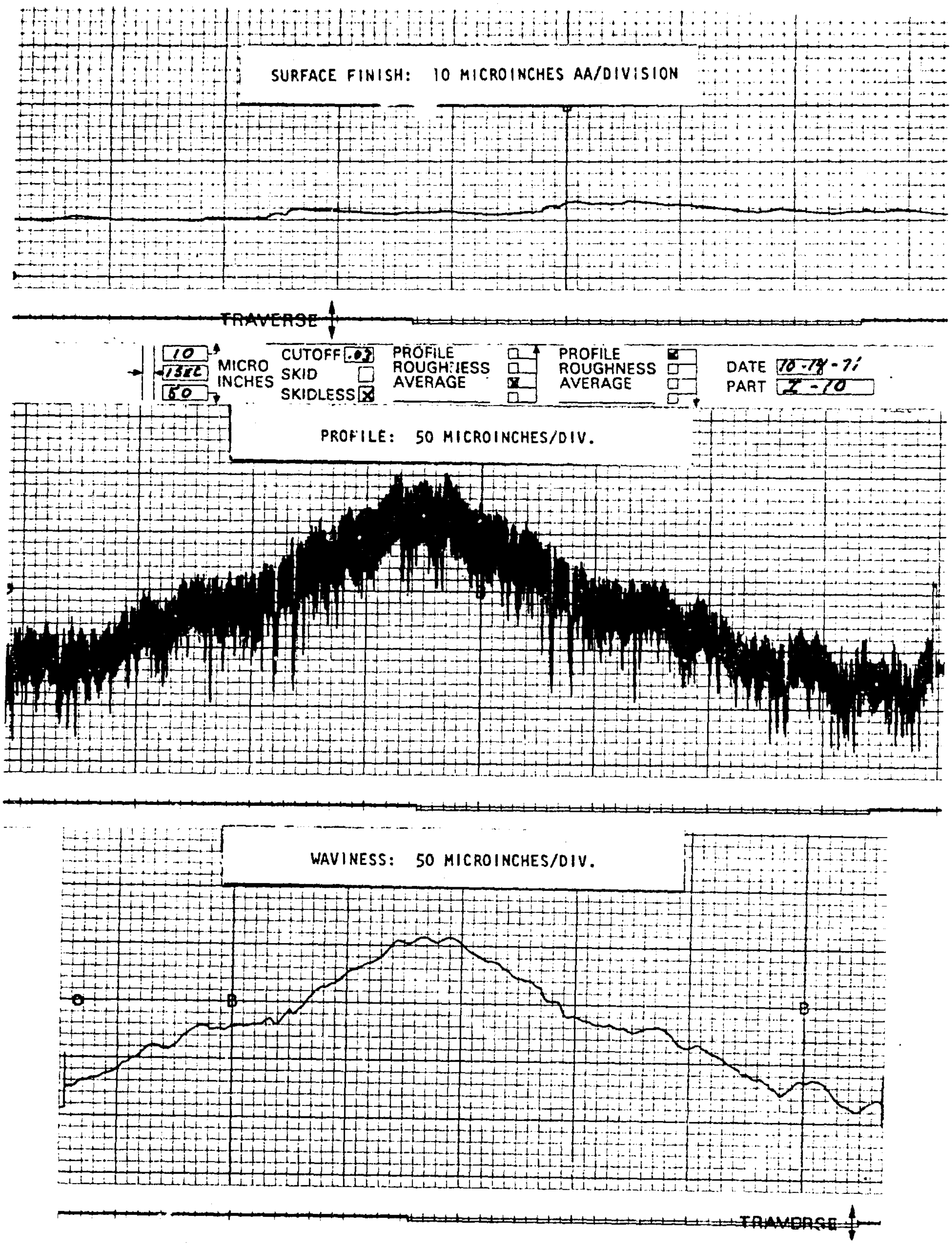


Figure 6. Profilometer traces showing profile, surface finish and waviness on gun drilled tube I-10.

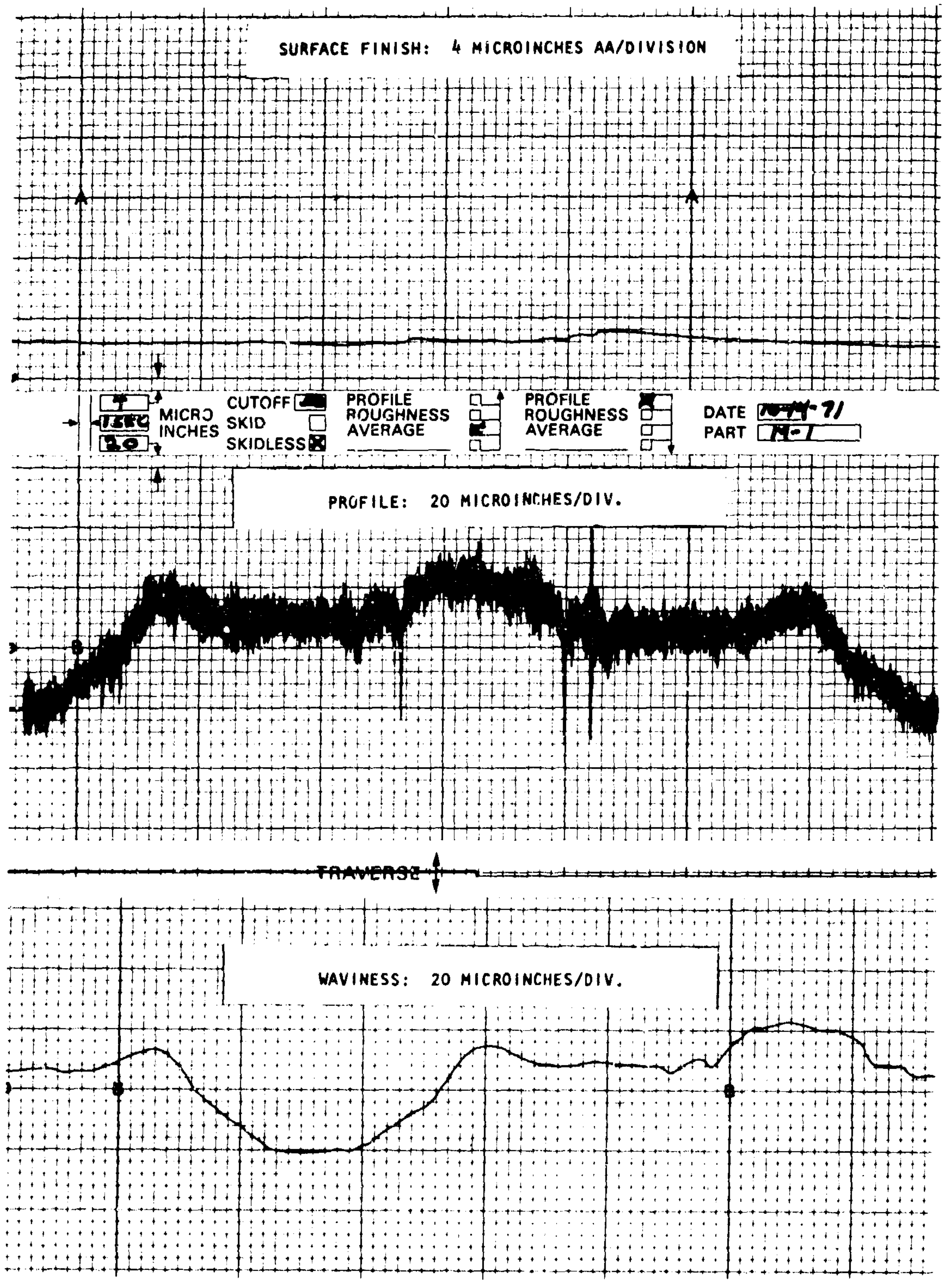


Figure 7. Profilometer traces showing profile, surface finish and waviness on gun drilled tube M-1.

3.22 ECM Stem Drilling

ECM stem drilling was evaluated as an alternative to gun drilling and hot piercing and extrusion which might become economically appealing for some advanced barrel materials. The major utility of this procedure is that gun tubes could be produced from materials which are virtually incapable of being drilled. Although feed rates are low, this process is electronically controlled and, therefore, could fit into a manufacturing scheme requiring relatively low direct labor costs with the exception of charging and discharging the stock.

Stem drilling was evaluated for Inco 718 and Vasco M-A using diluted sulfuric acid in the apparatus shown in Figure 8. The major features of this equipment are labeled in the figure and consist of the following:

1. Workpiece holder consisting of two knife-edge vee-blocks;
2. Coated titanium alloy tubular electrode of 0.156 inch outer diameter with a "foot" consisting of a flat end cutting surface with a knife edge finally established at 0.296 inch diameter;
3. Electrode feed mechanism comprised of a variable speed motor and control maintaining the electrode feed rate through a 150:1 precision gear reduction transmission;
4. Variable speed electric motor drive for electrode rotation;
5. External electrode bushing;
6. Electrolyte container and pumping system; and
7. ECM electronic control unit (not shown).

The operating conditions and results for stem drilling are presented in Table IV for Inco 718 and Vasco M-A. A dilute sulfuric acid electrolyte was selected for drilling of both alloys because of its desirable deplating characteristics necessary for electrochemical deep hole drilling. The voltage and pressure were established empirically based on experience and the requirement that runout would not exceed 0.001 inch/inch. The desired hole size of 0.320 inch diameter was approached by varying the machining parameters on the half-length setup pieces I-21 and I-22 to obtain a near optimum feed rate.

Subsequently, the hole was measured and the diameter of the working surface of the electrode was machined by an amount based on the measured oversize to finally achieve 0.320 inch. The difference between the performance for the preliminary evaluations on the half-lengths I-21 and I-22 and the full lengths I-3 and I-6 resulted from electrode rotation and improved bushing or guiding at the entry end of the full length blanks. No internal bushings were used in these

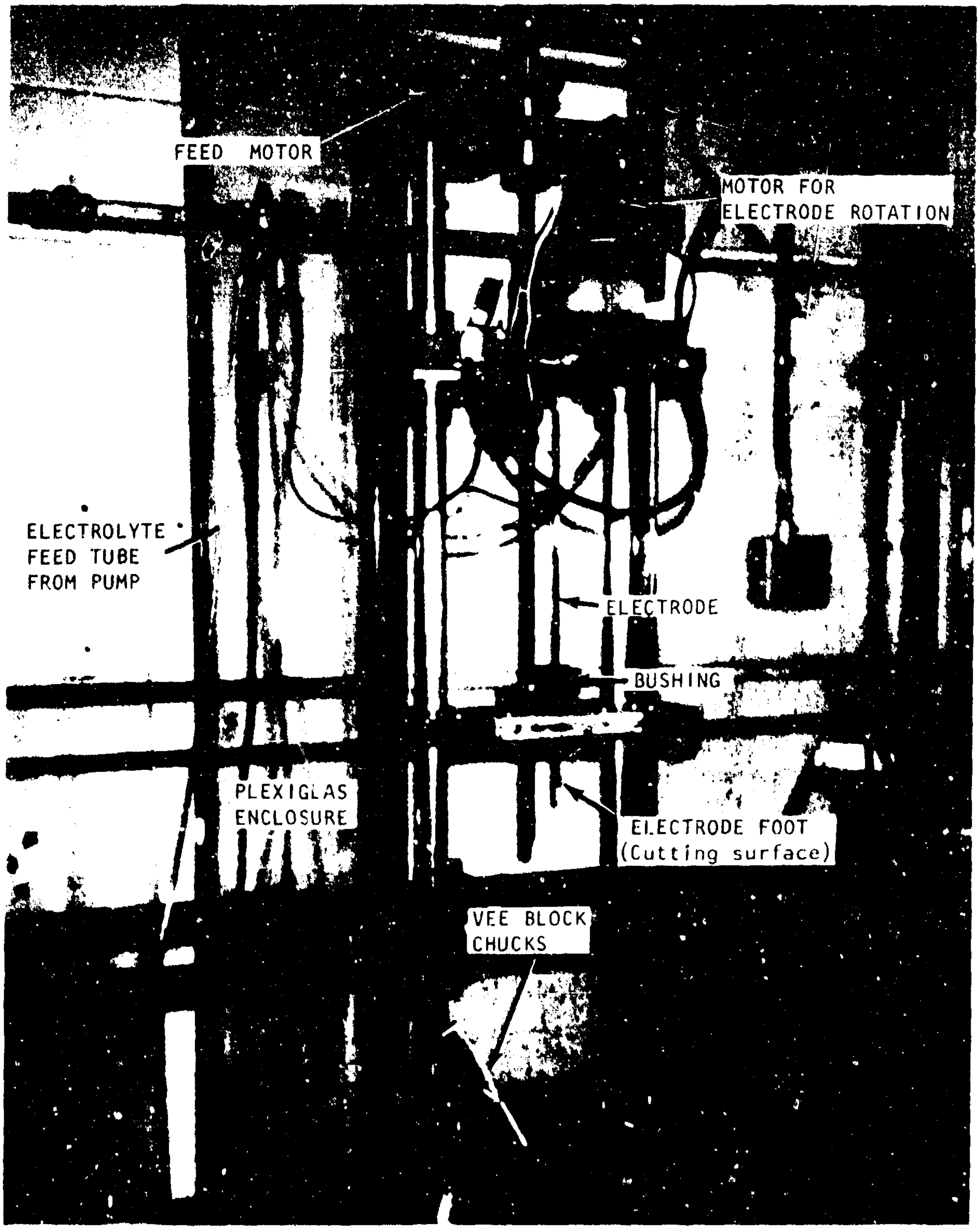


Figure 8. ECM stem drilling apparatus.

TABLE IV

ECM Stem Drilling Parameters and Results

Operating Parameters

Voltage (volts)	Current (amps/in^2)	Electrolyte Composition	Electrolyte Pressure	Electrolyte Temperature	Forward Time (seconds)	Reversing Time (seconds)	Reversing Voltage (volts)
8	1000	H_2SO_4 15v/o in H_2O	6 psi	88 to 90°F	17-20	0.05	5

Results

Specimen No.	Diameter Range (inch)	Total Indicated Runout of Bore from O.D. (In.)	Surface Feed Rate in/min.	Surface Finish (in.x10^{-6}AA)	Waviness Max. Ht. (inch)	Waviness Wavelength	Remarks
I-21*	0.3330±0.0003	0.0149	0.025	130	0.0011	0.4	
I-22*	0.3151±0.0002	0.0164	0.030	+	+	+	
I-3**	0.3184±0.0004	0.0062	0.027	55	0.0009	random	Electrode rotating at 12 rpm
I-6**	0.3209±0.0013	0.0037	0.027	++	++	++	" " "
M-21*	0.3894±0.0071	0.0038	0.027	135	0.0032	0.4	" " "
M-22*	0.3421±0.0058	0.0031	0.035	135	0.0028	0.4	" " "

* Half length blanks (11 inches long) used for setup and parameter evaluations
** Full length blanks
\+ Not measured, but appears similar to I-21
++ Not measured, but appears similar to I-3

trials. Internal bushings should improve concentricity, significantly reduce or eliminate waviness of the surface and permit greater feed rates. An electrode rotation of 12 rpm was used to maintain concentricity at a feed rate of 0.03 inch per minute for I-3, I-6, M-21 and M-22. Higher feed rates would be attainable with internal bushings which should permit greater electrolyte pressures and/or flow rates. However, it is doubtful that feed rates of 0.06 inch/minute could be achieved with a T.I.R. requirement less than 0.001 inch/inch and surface waviness amplitude less than 0.002 inch. A profilometer recording of the surface quality of the ECM barrel blank I-3 is shown in Figure 9. This measurement was made parallel to the axis of the bore over a 0.3 inch length approximately 1 inch from the electrode entrance side and appears characteristic of the ECM blanks. The major difference between the surfaces of gun drilled and ECM stem drilled blanks is the surface texture. ECM drilled blanks exhibit a random texture, whereas the gun drilled surface texture is periodic. This periodicity arises from the circumferential tool marks which can still be observed after swaging although swaging greatly improved the surface quality.

3.23 Hot Piercing and Extrusion

Hot piercing and extrusion was evaluated for tube fabrication with Inco 718. The tubes were hot pierced and extruded from 3.056 $\pm$ 0.001 inch diameter billets 5.10 inch long which were initially prepared with a 0.391 inch diameter centrally located hole and a chamfered nose to match the extrusion die. The billets were obtained from centerless ground bar stock of the desired diameter. This diameter was selected to provide a coated billet which closely fit the inner diameter of the extrusion container (3.125 inch) when heated to the temperature for extrusion. This condition is desirable because it would aid alignment of the billet in the extrusion tooling.

Billet preparation consisted of the following steps: 1) cutting to the approximate length; 2) facing both ends to achieve square ended cylinders 5.10 inch in length; 3) machining a 120° included angle chamfer with a 1.35 inch minimum diameter on one end; and 4) gun drilling a hole 0.391 inch diameter through the length of the billet. Gun drilling was performed under the conditions established by the results in Table II. The total indicated runout of the O.D. from the hole centers was less than 0.010 inch. A photograph of a billet prepared for hot piercing and extrusion is shown in Figure 10.

Hot piercing and extrusion was performed on a 700-ton Loewy extrusion press with some variation in tooling and billet designs and extrusion temperature to achieve the desired product. All of the trials started from billets prepared as described in the preceding paragraph. Any addition to these preparation procedures will be discussed only where changes were made. The extrusion dies were made of M-21 high speed steel double tempered to R_c54 to 56. These dies of 120° included angle with either 1.350 or 1.335 inch exit diameters were recessed to

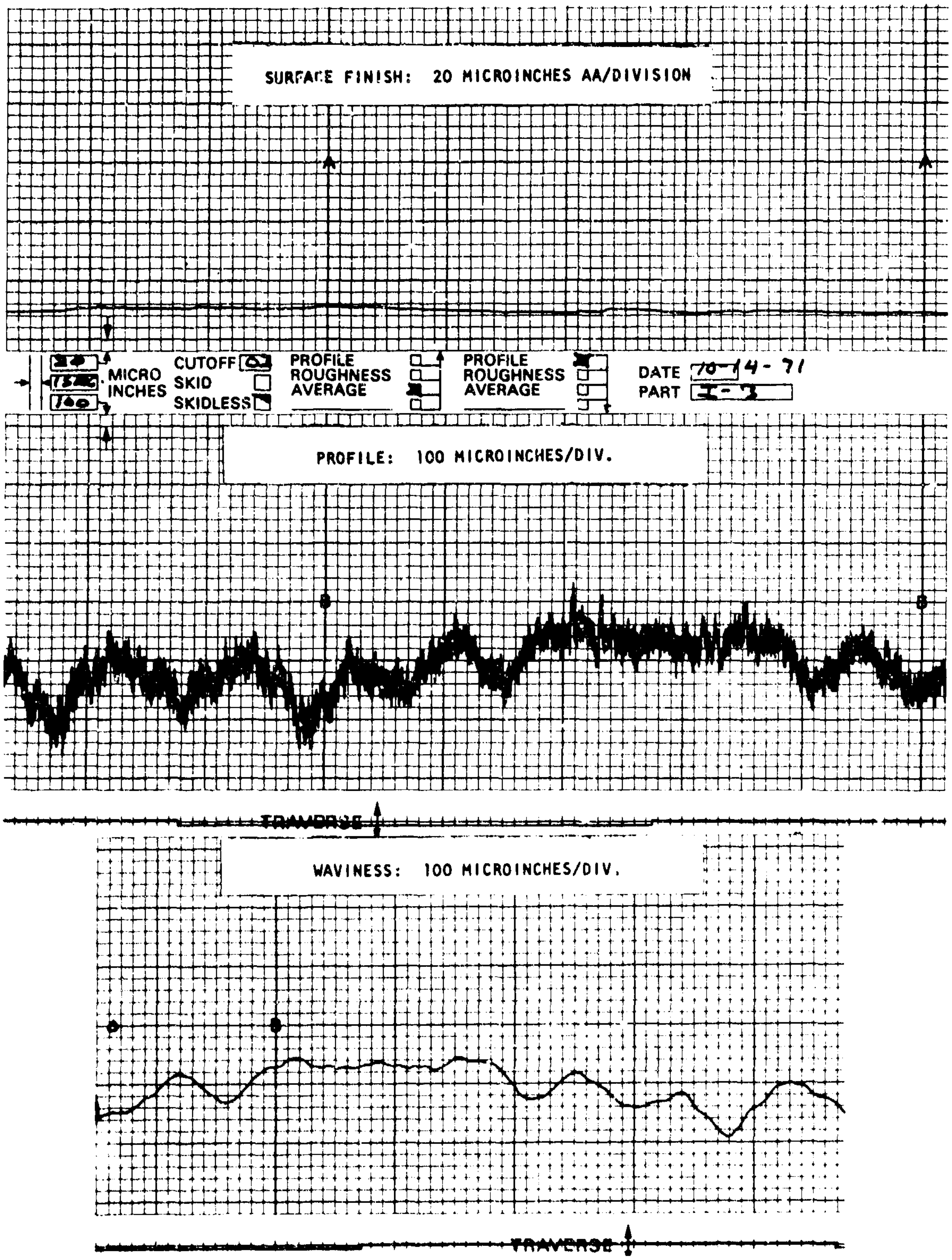


Figure 9. Profilometer traces showing profile, surface finish and waviness for the ECM drilled tube I-3.

Figure 10. Billet for hot piercing and extrusion.

accept a 0.020 inch thick plasma sprayed zirconia coating. This coating was polished to the finished thickness and die dimensions after spraying. The zirconia coating was used for insulation and to resist thermal mechanical wear. Furthermore, the coating provides an economic feature because it can be chipped off and the die can be sandblasted clean, recoated and reused. The selection of the 120° die angle for extrusion was based on analytical and experimental (3) results which have demonstrated that large die angles promote greater tensile stress (less compressive) near the interior of the extrusion. Therefore, during piercing, mandrel pressure and drag should be reduced with larger die angles, which should promote mandrel life. The 120° included angle appears to be a practical limit because larger angles tend to produce bursting of the billet nose.

The piercing mandrels were made from the molybdenum alloy TZM in the as-extruded and stress relieved condition and the high speed steel M-21 heat treated identical to the extrusion dies. The TZM and M-21 mandrels were used in two different sets of piercing evaluations. A TZM mandrel and standard dies used with conventional tooling for the first evaluations are shown in Figure 11. The TZM mandrel shown in this figure contains a 0.015 inch thick plasma sprayed and ground zirconia coating over its entire 4.5 inches of bearing surface. The bearing surface of the mandrel had a minimum diameter of 0.320 + 0.005/ - 0.000 inch and a taper of 0.015 inch/inch. The TZM mandrels were preapred by rough turning prior to coating to leave deep tool marks to aid adherence of the coating to the TZM especially in shear. The coating was subsequently ground to leave a highly polished surface. Three mandrels which were given the designation T-1, T-2, and T-3 were made under these conditions.

The standard tooling used with these mandrels did not provide sufficient guiding of the extrusion after exit from the die. Because the die exit had an opening taper to match the 2.0 inch inner diameter of the backup tooling, the extrusion had free lateral movement over ± 0.4 inch after exit from the die. This lateral movement was apparently produced by asymmetry of the extrusion caused by uneven chilling and lubricant breakdown resulting in bending of the product. Since the mandrel protruded into the extrusion beyond the die exit, any bending of the extrusion resulted in bending of the mandrel. The hot piercing and extrusion results in Table V show that although some good lengths of tube were obtained with this tooling, the extrusions were not straight and mandrel breakage occurred for all trials.

Special tooling and mandrels were designed for subsequent extrusions to maintain product straightness and avert mandrel breakage. The new tooling design is shown shcematically in Figure 12. This tooling was a modification of available standard extrusion tooling to provide 1.365 inch die exit and backup tooling inner diameters. This tooling was constructed by expanding the die opening from 1.330 at the land or minimum diameter to 1.365 inch at the die face or exit and through the die adapter and bolster. The tooling provided 4.5 inches of guiding surface 0.035 inch larger than the pierced and extruded tube. The length of guiding surface was longer than the maximum length of mandrel extension beyond the die. For this condition, the maximum possible bow of the tube in the guide could be .008 inch/inch when the mandrel extended beyond the die.

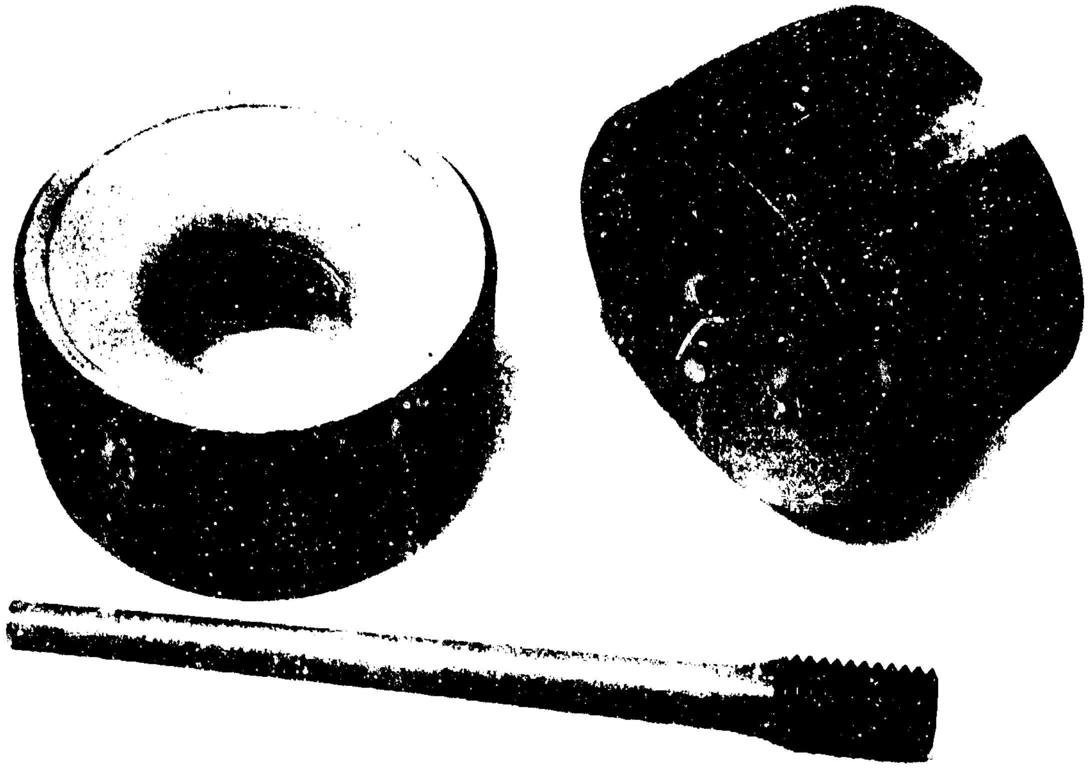


Figure 11. Standard dies and mandrel for initial hot piercing and extrusion evaluation with Inconel 718.

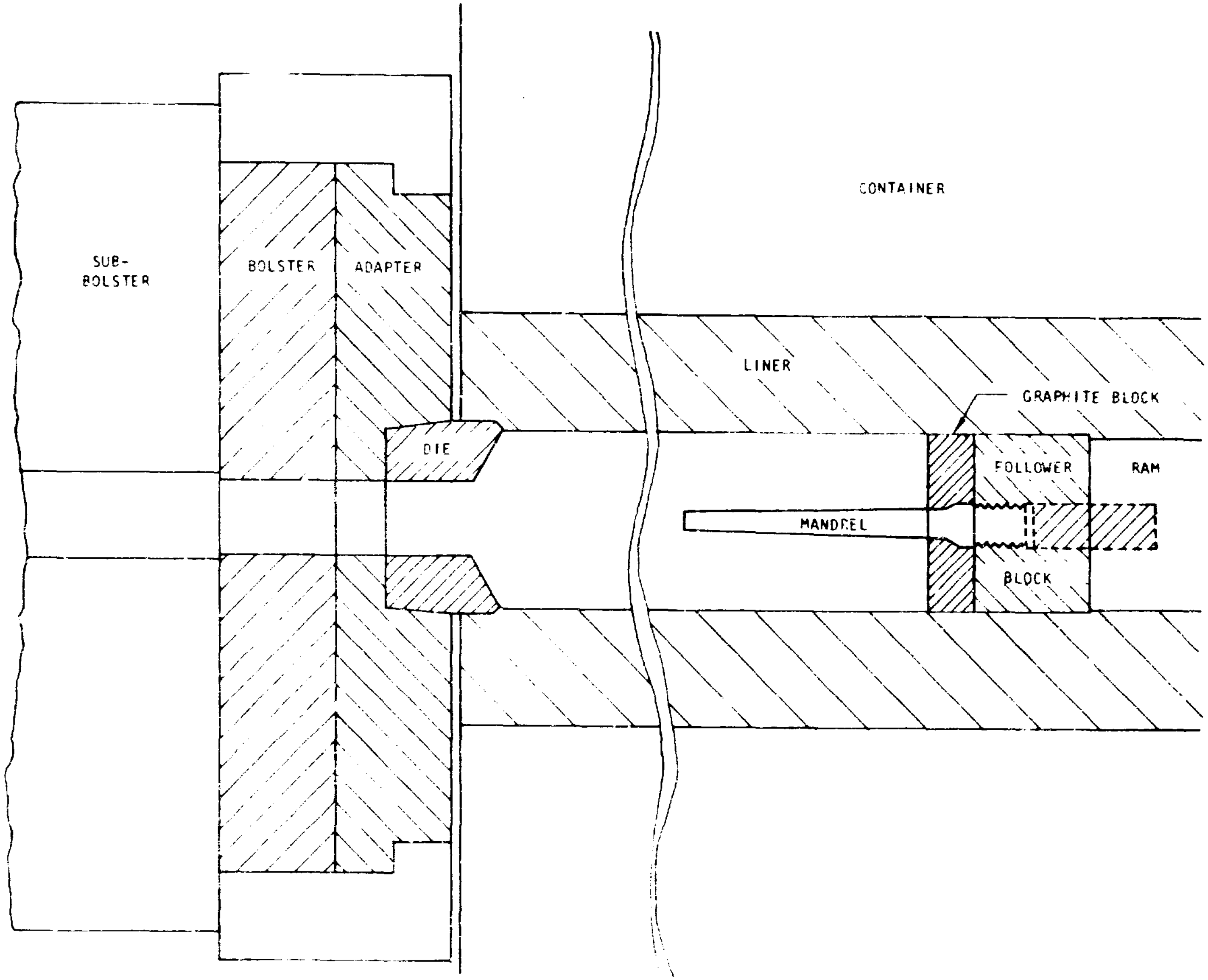


Figure 12. Improved tooling and mandrel (M-21 high speed steel) designs.

TABLE V

Hot Piercing and Extrusion Conditions and Results
for Inconel 718 Tube Fabrication

Mandrel No.	Billet No.	Extrusion Temperature (°F)	Ram Speed (in/sec.)	Maximum Extrusion Pressure (ksi)	Extrusion Diameter (inch)	Hole Dia. (Max./Min.) (Inch)	Max. Bow (In.)	Remarks
T-1	S-3	2025	1.8	133	1.306	-	1.62	*Mandrel broke
T-2	S-7	2025	2.4	138	1.316	0.345/0	1.95	*Mandrel broke
T-3	H-1	2000	2.4	139	1.330	0.375/0	1.74	Mandrel broke
M-1	S-1	2000	6.0	131	1.297	0.592/0.309	0.087	Overheated adiabatically and cracked
M-2	S-2	2000	1.8	138	1.299	0.581/0.320	0.890	
M-3	S-5	2000	1.8	139	1.304	0.410/0.322	0.105	

* Billets were carried on the mandrels into the liner and against the dies.

The M-21 steel mandrels used with the redesigned extrusion tooling are shown in Figure 13 in the as-coated condition ready for use. The preparation procedure for these mandrels differed from the procedures used for the TZM mandrels. Included tapers of 0.060 in/in were used with mandrel Nos. M-1 and M-2 and 0.030 in/in for Nos. M-3 and M-4. Although all mandrels were coated with zirconia, the M-21 high speed steel mandrels were finished by grinding to produce a 10 to 20 microinch AA finish prior to coating. A 0.020 inch thick coating was applied and subsequently used without polishing. This procedure was adopted to permit the coating to pull off during piercing to reduce the load transfer by shear to the mandrel. A zircon coating was also investigated for reducing the effects of heat transfer on mandrel performance. This coating was applied by dipping the mandrels in a slurry of the following composition: 80 weight percent -325 mesh (8 to 12 micron particle size) zircon ($ZrO_2.SiO_2$) powder plus 20 weight percent colloidal silica (30% SiO_2 in water). The coating was air dried for one hour at 85° to 87°F to provide a hardened coating similar to concrete with 20 to 30 volume percent porosity and a tensile bend strength in the range of 1000 to 2000 psi. The coating thickness per dip was 0.010 to 0.012 inch. The actual coating thicknesses which were used are described in Table VI with other mandrel dimensions. Although the primary purpose for the coating was thermal insulation, the zircon coating was selected because of porosity and friability. This character of the coating resulted in its crumbling and extension with the tube during extrusion to permit tube production with diameters smaller than the mandrel as shown by the results in Table V. The moderate strength of the zircon coating appeared to be sufficient to provide positive location of the mandrel and the billet.

The procedure established for tube extrusion with both mandrel and tooling designs consisted of the following steps:

1. Selection of a billet diameter which closely fitted the liner at the extrusion temperature.

2. Chamfering of the billet nose to match the extrusion die and gun drilling a hole located within ±0.005 inch of the centerline.

3. Coating the die and mandrel with a mixture of 50 volume percent -325 mesh graphite powder in waterglass and allowing the mixture to air harden at 200°F for 1/2 hour.

4. Threading the mandrel to the follower block accurately connected to the press ram as shown in Figure 12.

5. Placing at the back of the mandrel a 1 inch thick piece of graphite with a 3 inch outer diameter and an inner diameter to match the mandrel. The purpose of this graphite was to completely eject the tube from the die after extrusion.

Figure 13. Coated M-21 high speed steel mandrels.

TABLE VI

M-21 High Speed Steel Piercing Mandrels

Mandrel No.	Length (inch)	Dia. (inch) Max./Min.	Coating Thickness (in.) Zirconia	Zircon	Hardness R_C After Piercing*
M-1	5.38	0.565/0.310	0.020	0	32/41
M-2	5.38	0.565/0.310	0.020	0.040	45/47
M-3	5.38	0.440/.310	0.020	0.040	32/49
M-4	5.38	0.440/0.310	0.020	0.060	not used

* Front/back hardness values

6. Swabbing of the die, liner and mandrel with lubricant (Fiske Brothers No. 604, Hot Die Lubricant).

7. Heating of the billet to the desired extrusion temperature (45 minutes).

8. Insertion of the billet into the liner at 800°F and against the die.

9. Piercing and extrusion by bringing the ram forward to engage the billet with the mandrel to fabricate the tube.

Mandrels T-1 and T-2 (Billets S-3 and S-7) were used to ride the billet into the extrusion press liner. However,this was not completely successful apparently due to the prolonged contact time of the billet and mandrel which could lower the mandrel strength. For the remainder of the extrusions, the rear of the billets were machined with a 0.25 inch 45° chamfer to aid location of the mandrel. Before heating, the billets were coated with a mixture of Corning Commercial Glass No. 7740 with 10 weight percent boric oxide plus binder and allowed to dry. The coated billet was then heated in air for 45 minutes at the temperatures listed in Table V.

The results in Table V clearly demonstrate the utility of the guide tooling and the improved mandrel designs. None of the M-21 mandrels failed although the hardnesses (Table VI) measured after use indicated that they would require heat treatment before subsequent reuse. The straightness of the tubes are significantly improved with the guiding tooling. However, the bow (measured as the maximum displacement from a straight edge lying along the tube) was not completely eliminated by the guide tooling. The bow which did occur probably was caused by the extrusion decelerating against the sand in the runout tube assembly of the press.

Typical extrusion results for the guided tooling and M series mandrels are shown in Figures 14 and 15 for billet S-5. Figure 14 shows the as-extruded tube, a radiograph of the tube and a magnified longitudinal segment of the bore surface. The extruded tube has a rough striated surface typical of a hot extruded superalloy. The radiograph of the 1.330 inch diameter tube indicates some waviness of the surface probably caused by uneven crumbling of the mandrel coating. Surface cracks are also apparent. These cracks, which were not always observed, appeared to be small chevron or centerburst defects (3) which could be averted by using larger reductions, larger mandrels, and smaller die angles. The possible occurrence of these cracks would necessitate full inspection of the product during production fabrication. With the exception of the occasional occurrence of the cracks, the bore surface finish produced by piercing was good for this type of product as shown by Figures 14c, 15 and 16. The bore surface shown in Figure 14c had a roughness of 28 microinch AA and waviness of 700 microinch measured parallel to the extrusion direction. The tube cross section in Figure 15 demonstrates the concentricity attainable by hot piercing and extrusion. Measurements taken on this section in three directions at 120° provided the following:

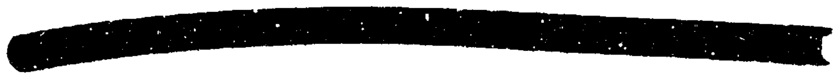


Figure 14a. Hot Pierced and Extruded Tube S-2.

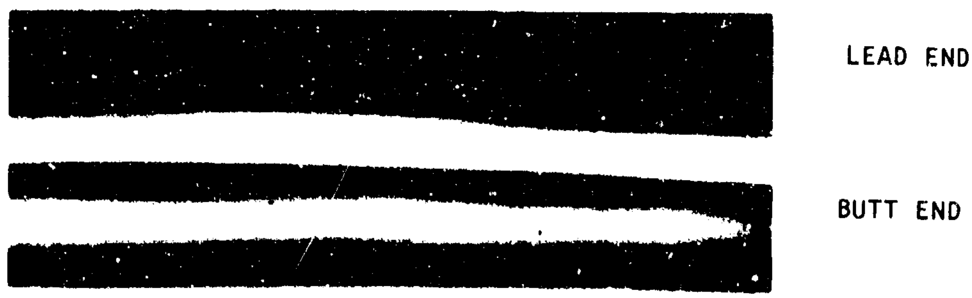


Figure 14b. Radiograph of Lead and Butt Ends of Tube S-5.

Figure 14c. Longitudinal Section of Tube S-5.

Figure 14. Hot pierced and extruded Inco 718 tube.

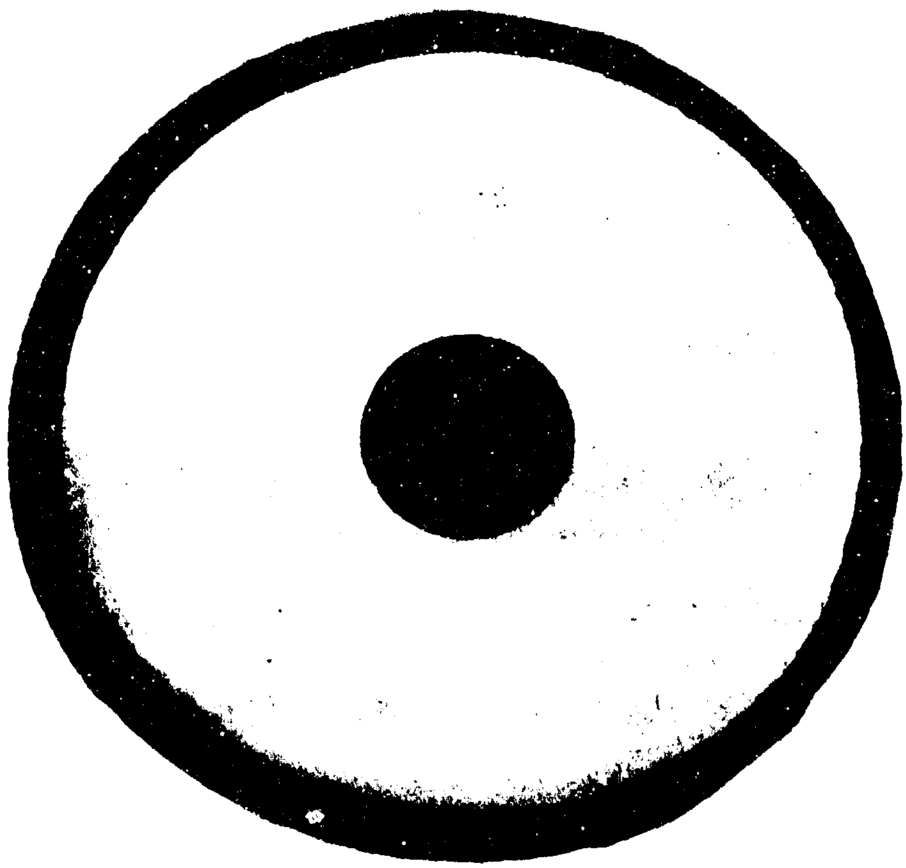


Figure 15.   Cross section of hot pierced and extruded tube S-5.

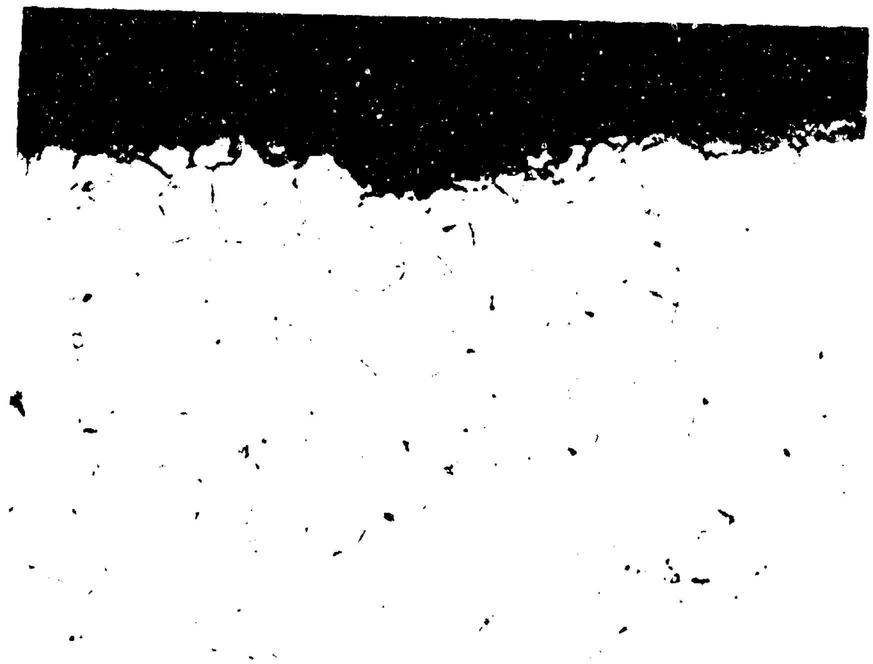


Figure 16. Micrograph at bore of hot pierced and extruded tube S-5.

Measurement Direction	O.D. (inch)	I.D. (inch)	I.D. (inch)	O.D. (inch)
0°	0	0.4842	0.8296	1.3018
120°	0	0.4809	0.8259	1.3115
240°	0	0.4830	0.8291	1.3140

The micrograph shown in Figure 16 is a magnified section of Figure 15 showing the quality of the bore surface and the microstructure. In general, 0.004 inch minimum should be removed to clean and insure a structurally sound bore surface. There was considerable grain growth during extrusion as shown by comparison of Figure 16 with Figure 3. This growth would affect barrel performance, but could be minimized by extruding at temperatures below 2000°F. The measured extrusion pressures were in the range of 130,000 to 140,000 psi for a nominal 4:1 reduction. Compromises between reduction and temperature would have to be made to keep the pressure below 180,000 psi, typically the maximum capability of most extrusion presses. It is doubtful that reductions greater than 10:1 at temperatures below 1900°F could be achieved. Because the hardnesses of the as-extruded tube were in the range of R_b 94 to 97, it might be possible to avert solution treatments. Therefore, the as-extruded bars could be aged at relatively low temperatures (below 1400°F) either before or after swaging or barrel finishing.

The final preparation procedures of the extruded tubes consisted of the following steps:

1) Cold straightening of the outer diameter to within 0.0015 in/in;

2) Cutting of the blanks to the approximate desired length using an abrasive cutoff machine;

3) Solution treating (1750°F for 1 hour) in salt or protective atmosphere followed by a rapid air cool;

4) Facing the blanks to the desired length (22.5 ± .3 inch);

5) Rough grinding the outer diameter of the bars on centers to achieve complete removal of the as-extruded surface;

6) Internal stock removal (gun reaming or gun drilling) to prepare the bore surface for swaging.

Cold straightening was performed on a 20-ton hydraulic arbor press with adjustable vee blocks. About 15 minutes were required to straighten the average tube; however, production straightening machines could be used to reduce this time appreciably. Rough O.D. grinding of the tube on centers was necessary to produce a completely round blank. The lack of roundness of the outer diameter in a few small areas resulted from uneven lubricant breakdown during initiation of extrusion and a small amount of irregular die wash. This stock removal was required for alignment during subsequent bore surface preparation for swaging. The bore surface was prepared by gun drilling by removing a minimum of 0.010 inch from the inner diameter. ECM bore preparation using a very long electrode might have been very useful for final bore preparation but was not investigated for this application.

3.24 Filled Billet Extrusion of the Cobalt-Base Alloy

The filled billet technique (4) for extrusion of tube was evaluated in two phases for the cobalt-base alloy. The first phase was essentially a one-half scale process evaluation to establish both the processing parameters and heat treatments necessary for fabrication of full size blanks, which comprised the second phase.

Some problems were encountered in preparation of this alloy powder which subsequently affected the total processing sequence. The initial developments leading to the selection of this alloy were based on Federal-Mogul water atomized powder (5). Early attempts to use this powder resulted in low carbon and relatively high oxygen concentration (3500 ppm). After some preliminary evaluations, it was decided that the high oxygen concentration would not be entirely suitable for the first use of this material as a barrel because of the toughness requirement and more recent swageability studies performed by the Army after initiation of this program. Therefore, water-atomized powder was mixed with 50 weight percent solids to make the necessary 200 pound charge for hydrogen atomization to obtain high purity powder. Although the possibility of a boil was anticipated and precautions taken, a severe boil resulted during induction vacuum melting of this powder + solid charge resulting in a total yield of 134 pounds of -20 mesh powder rather than the near 200 pounds anticipated. Therefore, a very careful process evaluation was performed to completely establish the conditions necessary for the maximum yield on gun tubes.

3.241 Process Evaluation

A one-half scale filled billet was extruded to evaluate the processing parameters for barrel tube fabrication. The design of this billet is shown in Figure 17. This extrusion was made only for process evaluation with 5 pounds of -20 mesh powder which possessed a loose density

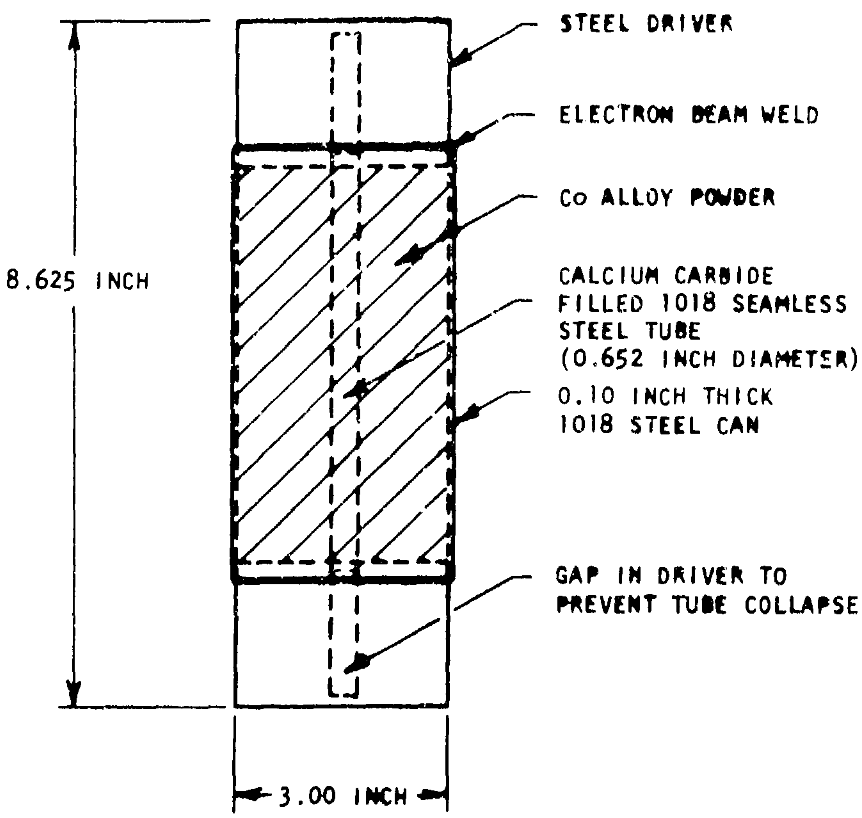


Figure 17. Schematic diagram of filled billet for production of one-half scale cobalt alloy barrel blanks.

of 58% of theoretical. This density and the powder volume determined the required travel of the drivers during the upsetting stage of extrusion. The drivers have been drilled to accept the I.D. tube during upsetting to avoid column buckling which would otherwise occur. With this technique 83 inches of 0.667 inch O.D. x 0.165 inch I.D. extrusions were made with the following processing conditions:

1. Billet heating: Barium chloride salt bath for 2 hours at 2000°F ± 15°F.

2. Extrusion conditions:

   a) 90° die angle,

   b) 2.8 in./sec. ram speed,

   c) 800°F container temperature, and

   d) Fiske Bros. Hot Die Lubricant No. 604 on the liner and die.

The maximum extrusion pressure was 93,000 psi.

The billet was extruded with a tail stub left in the die to promote straightness by not allowing the extrusion to accelerate and impact against the sand in the runout tube. This stub was hot sawed from the remainder of the extrusion in the extrusion press. Subsequent hardness measurements showed that the hardness variation from front to tail was 44 to 55 R_c respectively. The lower reading could have resulted from overaging in the sand, whereas the harder tail end was exposed to a slow air cool. Microstructures typical of the midlength position (R_c 44) of the extrusion are shown in Figures 18 and 19. These micrographs exhibit relief at the O.D. and I.D. of the tube, which is indicative of the hard carbide particles. In both sections, grain boundaries are nearly impossible to reveal; however, careful microscopic evaluations indicated that the average grain size is about 4×10^{-4} inch. The microstructure near the bore differs from that at the mid-thickness region mainly in carbide concentration. It was observed that the steel tube used for fabricating the bore had been carburized by the adjacent cobalt alloy. Since the loss of carbon could affect the barrel performance, an electron microprobe trace (0.001 inch diameter beam spot) was taken across the transverse section to determine the depth of carbon depletion, the amount of material to be removed during subsequent conditioning. This traverse taken from the bore surface to the blank-can interface at the O.D. is shown in Figure 20. Because of the high resolution of the electron microprobe, a large

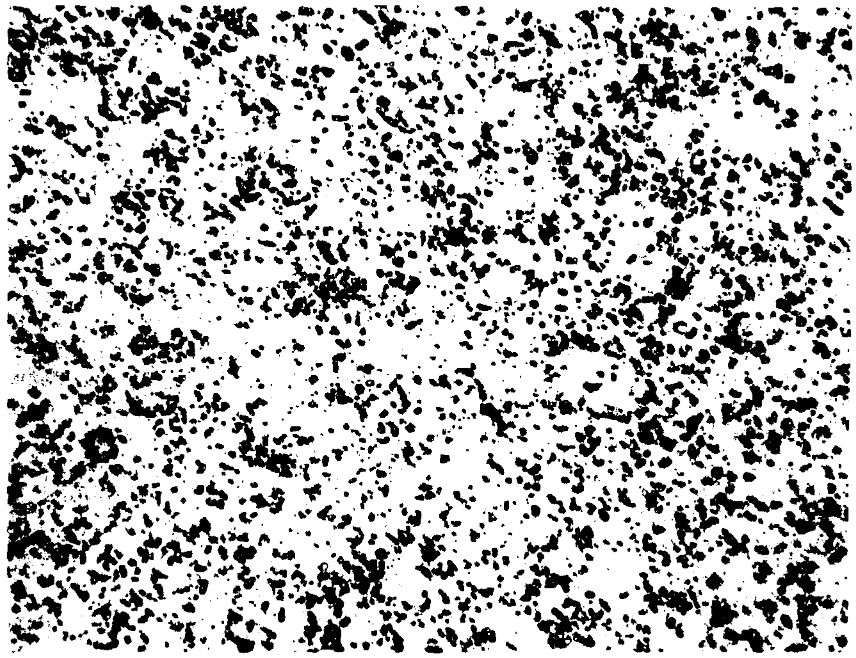


Figure 18a. Transverse section at mid-thickness position of cross-section. 250X.

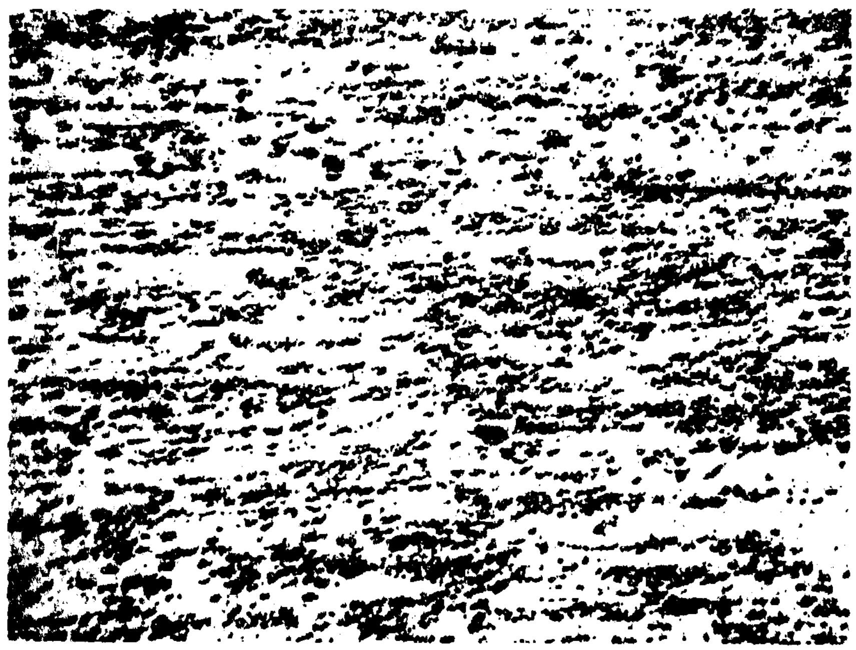


Figure 18b. Longitudinal section at mid-thickness position of cross-section. 250X.

Figure 18. Micrographs at mid-thickness position of cobalt alloy extruded tube.

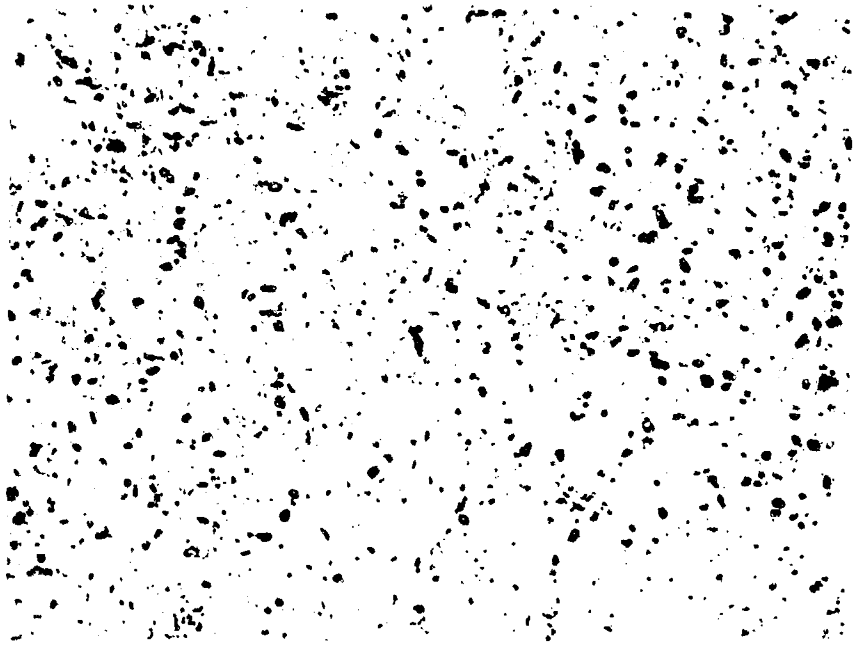


Figure 19a. Transverse section at bore surface. 250X.

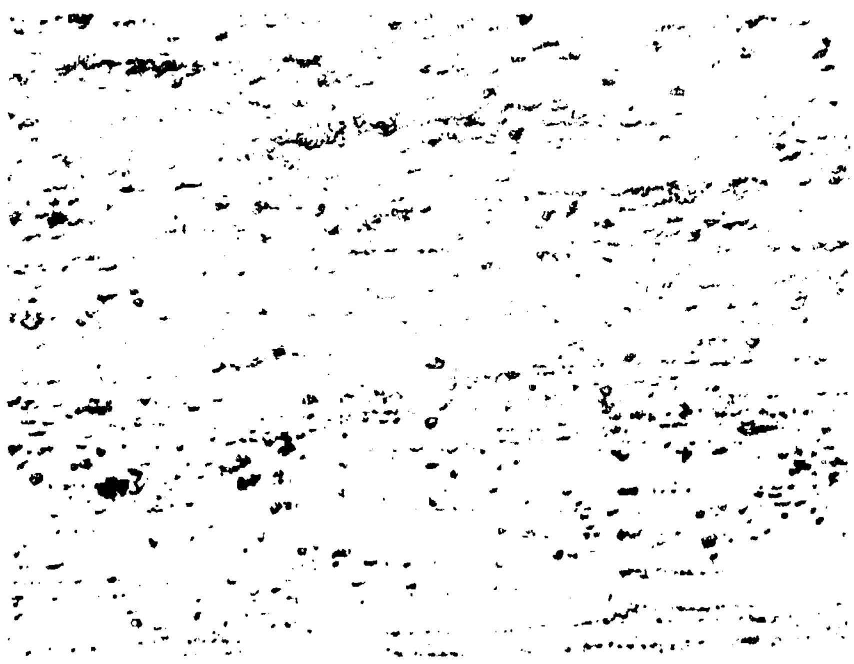


Figure 19b. Longitudinal section at bore surface. 250X.

Figure 19. Micrographs at bore surface of cobalt alloy extruded tube.

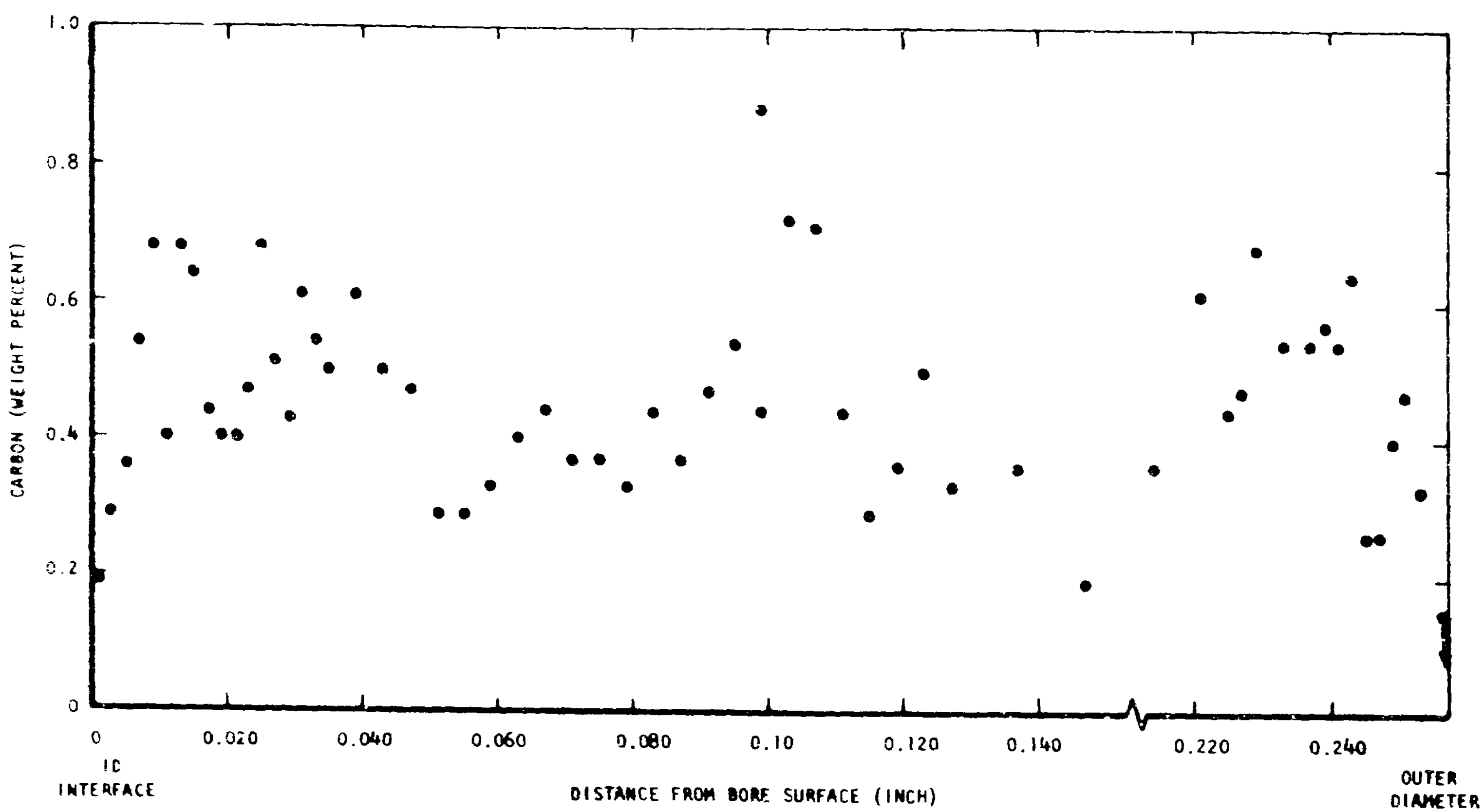


Figure 20. Electron microprobe results for carbon across cobalt alloy extruded tube.

variation in the carbon determinations was anticipated as shown in Figure 19. The large beam spot diameter, 0.001 inch, was used to achieve more of an averaging effect and, thereby, reduce the variations. Obviously, the variations were caused primarily by the beam intersecting varying amounts of carbide particles and matrix at each position on the traverse. The average carbon concentration measured with the microprobe was 0.47% with a standard deviation of ±0.14% for 55 measurements, whereas the wet chemistry reading was 0.54%. The most significant observation from Figure 20 was the drop of carbon composition associated with only 0.005 inch of the material adjacent to the bore surface. This amount can be easily removed by chemical and mechanical conditioning of the bore surface originally anticipated for the blank fabrication procedure.

The dimensional quality of the consolidated extrusion can be observed from Figure 21, showing a magnified cross section of the as-polished blank. The dimensions of the cobalt alloy tube in this cross section based on the bore diameter for defining the centerline and taken in three directions at 0°, 45° and 90° from vertical in the lower right hand quadrant of Figure 21 are as follows:

Direction	O.D. (inch)	I.D. (inch)	℄ (inch)	I.D. (inch)	O.D. (inch)
0°	0.3326	0.0827	0	0.0827	0.3306
45°	0.3332	0.0825	0	0.0825	0.3345
90°	0.3326	0.0842	0	0.0842	0.3371

In order to determine the effect of extrusion parameters and heat treatments on hardness, aging studies were performed on the Co-base alloy. The results of this evaluation are presented in Table VII. All of these data were obtained from one-half inch long segments of the extrusion in the specified conditions with the corresponding as-received hardnesses listed in the table. Aging and "solutioning" or high temperature annealing treatments were performed in air at the specified cumulative times and were always followed by a water quench. All of the recorded hardnesses are the average of three readings which had to agree to within ± 1 R_c or subsequent sets of three readings were obtained until this agreement was achieved.

The results in Table VII for aging in the 800°F to 1200°F range indicated that the tail section of the extrusion at R_c 54 ± 1 was nearly overaged, whereas the mid-section material at R_c 45 ± 1 still possessed a significant aging potential. Although the tail section was air cooled

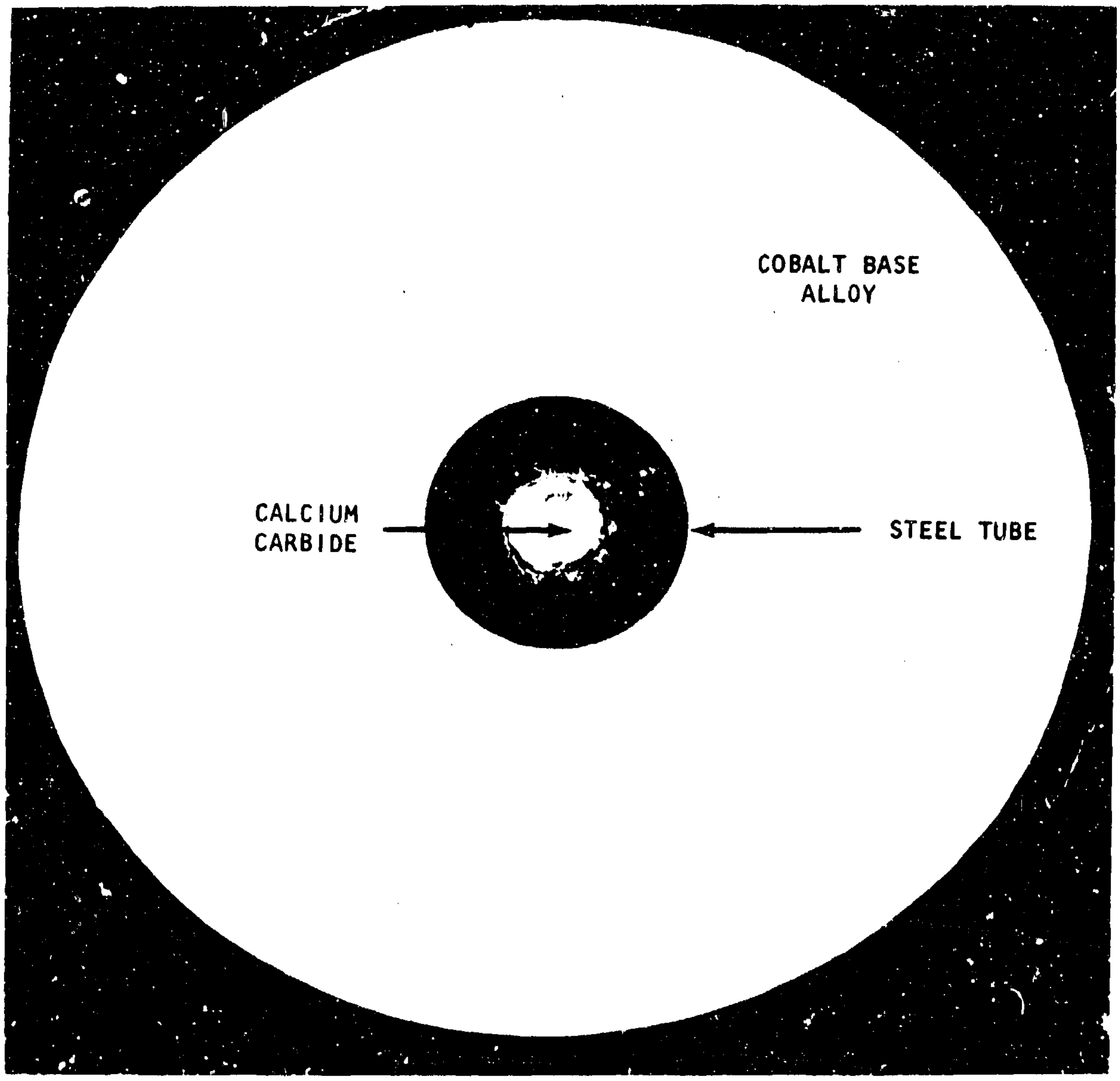


Figure 21. Cross section of cobalt alloy extruded tube.

TABLE VII

The Effect of Heat Treatments on Hardness
of the Cobalt Base Alloy

Specimen No.	Condition	Temp. (°F)	As Received	15 Min.	30 Min.	60 Min.	120 Min.	Remarks
CX-1A	As extruded, mid-length	800	45.1	49.1	51	52.9	54.3	Subsequently solution treated at 1800°F
CX-1B	As extruded tail section	800	53.0	54.1	54.2	54.8	52.8	
CX-2A	As extruded mid-length	1000	45.1	56.2	57.3	-	58.2	Subsequently solution treated at 2000°F
CX-2B	As extruded tail section	1000	55.3	55.2	57.3	-	-	
CX-3B	As extruded tail section	1200	54.3	55.2	55.6	55.4	53.5	Subsequently solution treated at 2200°F
HCX-4	As extruded tail section	1800	52.6	-	-	47.7	-	Subsequently aged
HCX-5	" "	2000	53.6	-	-	46.3	-	
HCX-6	" "	2200	53.3	-	-	46.7	-	Subsequently aged
CX-1A	As aged	1800	54.3	-	-	47.3	-	
CX-3B	As aged	2200	53.5	-	-	46.8	-	
HCX-4	As solution treated	1000	47.7	-	-	57.0	-	
HCX-6	" "	1000	46.7	-	-	60.3		

inside the backup tooling of the extrusion press during sawing of the stub, this tooling was maintained in the temperature range of 800°F to 200°F due to conduction from the heated container. Therefore, significant aging could have occurred at the tail section, whereas the midsection, although sand cooled, would have experienced a lower average temperature.

High temperature heat treatments at 1800°F, 2000°F and 2200°F for one hour did achieve significant solutioning as shown by the results for specimens HCX-4, -5, and -6, and CX-1A, -2A and -3B. Micrographs of samples prepared to determine grain size and carbide morphology and distribution after the 1800°F and 2200°F solutioning treatments are shown in Figures 22 and 23. The structure shown in Figure 22 after the 1800°F annealed exhibited a general coarsening of the carbide particles with a resulting randomization of their distribution when compared with the as-extruded material. This observation indicated that solutioning was not complete at 1800°F. Although grain boundaries could not be discerned, the acicular structure in this micrograph may be confined to individual grains. This acicular structure has the appareance of martensitic-type reaction product. However, because the metallography of this alloy is virtually unexplored, it is almost impossible to discuss the microstructure quantitatively with the exception of grain and carbide size and morphology. The micrographs in Figure 23a and b show the structure at two levels of focus necessary for contrast to show grain boundaries and carbide particles because of polishing relief about the carbide particles. Although similar focusing procedures were attempted with the structure at 1800°F, no significant differences in resolution were discerned. When compared with the as-extruded and the 1800°F annealed structures, the 2200°F annealing treatment appeared to produce continued carbide growth and delineation of grain boundaries possibly by precipitation of second phase particles. However, for both annealing treatments the carbide and grain sizes were small indicating that neither treatment should adversely affect swageability. Since the as-quenched hardnesses were similar, it was decided to use the 1800°F anneal after extrusion to reduce the hardness of the blanks for subsequent swaging.

3.242 Full Size Barrel Fabrication

The full size barrel fabrication by the filled billet technique was performed under conditions established by the 1/2 scale process evaluation with some modifications to improve the yield. The need to achieve maximum yield resulted from the relatively low yield of powder due to the severe boil during melting. The tubes were produced in two identical 62 pound lots using the assemblies described in Figures 24 and 25. The procedures which were followed are described in the following.

Two identical low carbon steel (1010) billet assemblies were prepared as shown in Figure 24. The component designs were based on a homogeneous reduction to produce tubes of 0.310 inch inner diameter and a composite outer diameter of 1.30 inch. After machining, the assembly

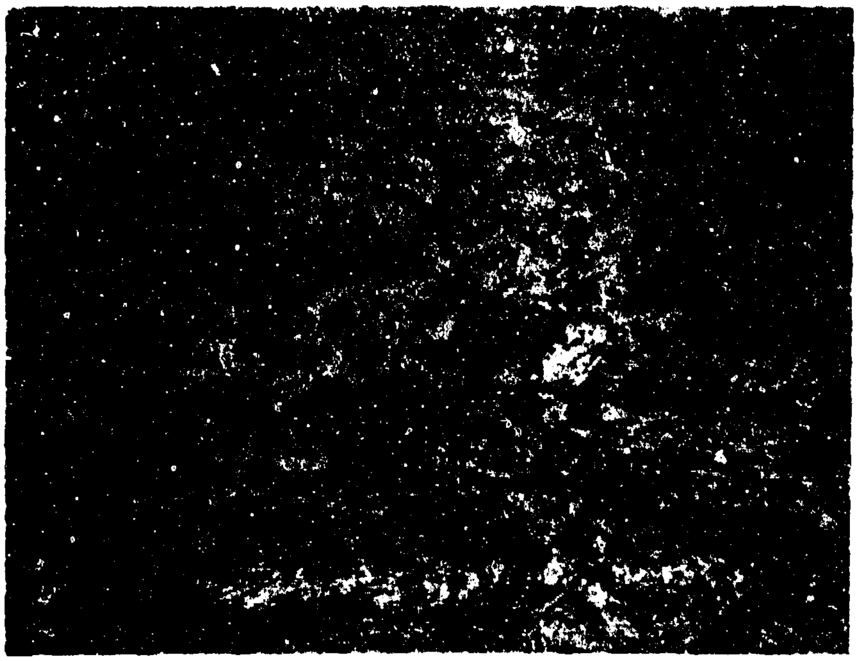


Figure 22. Longitudinal section of specimen HX-4 after a 1 hour anneal at 1800°F followed by a water quench. 500X.

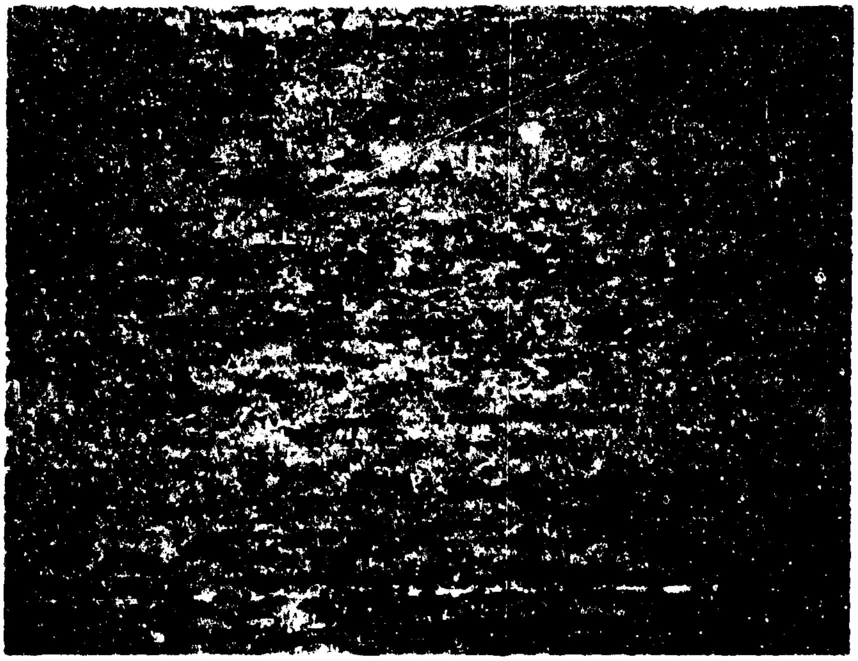


Figure 23a. Focus established to show carbide morphology, distribution and size.

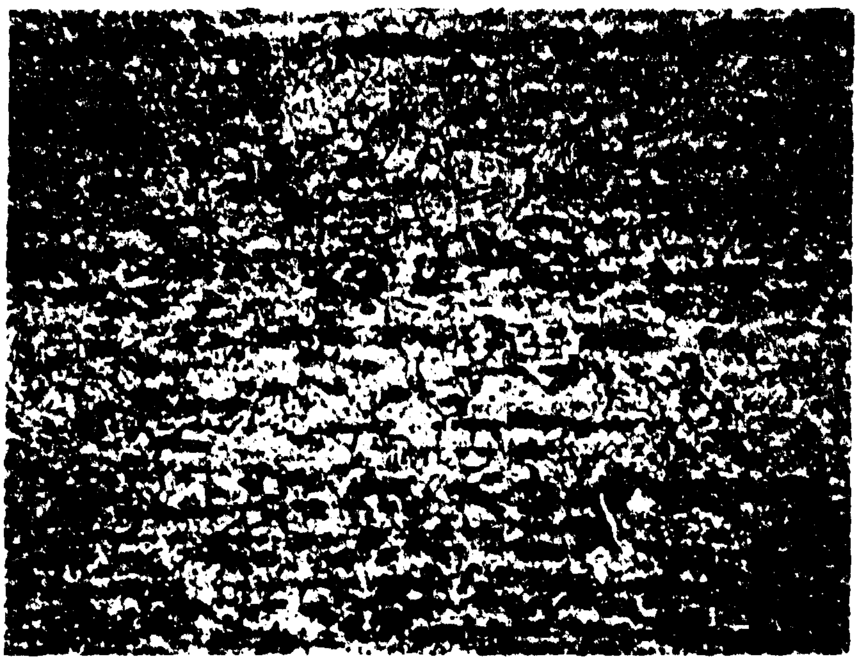


Figure 23b. Focus established to show grain boundaries.

Figure 23. Longitudinal section of specimen HX-6 after a 1 hour anneal at 2200°F followed by a water quench. 500X.

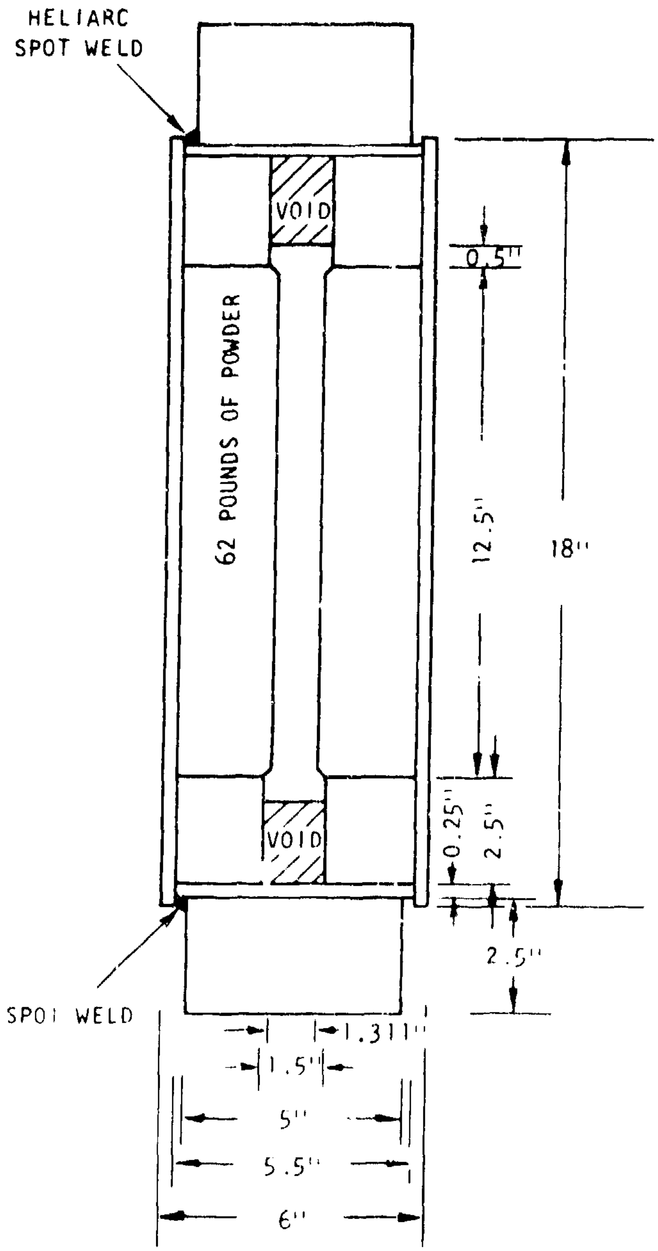


Figure 24. Can used for initial filled billet consolidation of the cobalt base alloy.

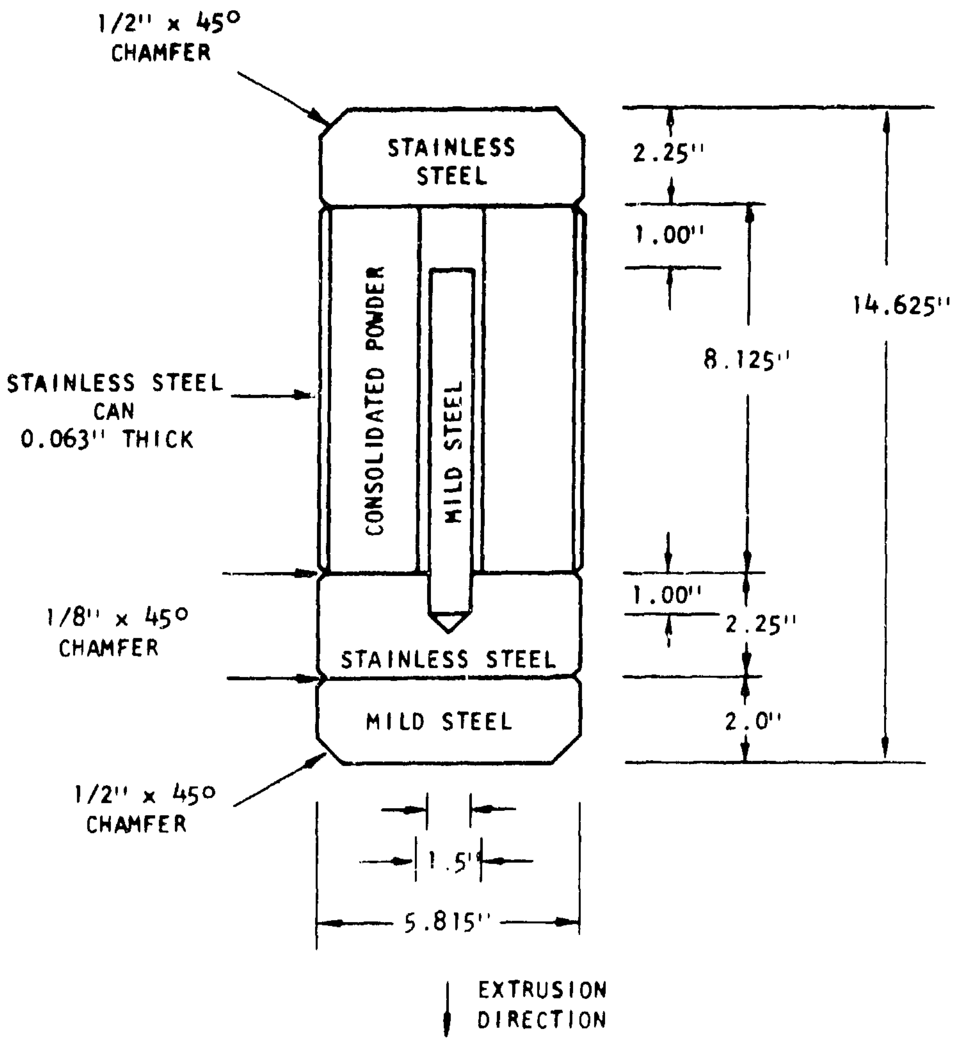


Figure 25. Can used for filled billet extrusion of the cobalt base alloy.

components were cleaned in trichloroethylene, sand blasted with alumina grit and cleaned again in trichloroethylene. One end of the can was assembled, Heliarc spot welded to fasten this partial assembly and the core was then inserted and aligned. Each of the two partial assemblies was filled with 62 pounds of the -20 mesh powder which had a composition in weight percent of 0.54 carbon, 13.10 tungsten, 54.12 cobalt and 32.27 iron and a bulk density of 5.66 gm/cm^3. Each of the two cans was then completely assembled, placed into the chamber of an electron beam welding unit, and welded under a chamber pressure of 10^{-5} torr.

The sealed billets were subsequently heated to 2000°F in preparation for initial compaction. Heating was performed by placing the billets into graphite retorts to reduce oxidation of the steel can and placing this assembly into a furnace at 1500°F. In two hours the furnace reached 2000°F and was held at this temperature for an additional 40 minutes. Because of the need to obtain maximum yield from this powder, the billets were initially compacted, rather than extruded, in the extrusion press at 100 tons/inch^2 for 15 seconds in the liner at 800°F. A blank die was used for this operation. After consolidation the billets were allowed to cool in air.

The two consolidated billets were prepared for extrusion by turning on centers to remove the steel can, gun drilling a 1.50 inch center hole, cleaning and recanning for the new assembly shown in Figure 25. The components were cleaned, assembled, welded, evacuated, and sealed by the same methods used for the first billet. A stainless steel can was used for this assembly because a thinner can was required and, therefore, oxidation resistance and impermeability to the atmosphere were prime requirements. The heating procedures used for compaction were followed for extrusion. Extrusion was performed at a ram speed of 3 inches/sec. from a 6.180 inch diameter liner at 800°F through a 1.350 inch diameter die with a 90° included die angle. The maximum extrusion pressure was 144,000 psi. The uncoated alloy steel die exhibited wear which was indicated on the extrusion by longitudinal striations. Therefore, a new die was used for the next extrusion. During heating of the second extrusion, the refractory lining on the furnace began to spall which required removal of the billet and shutting down of the furnace because of safety considerations. The furnace was repaired and the second extrusion was performed under the same conditions as the first. After the extruded tube had cooled it was found to have cracked along its entire length. Although the tube appeared to have cracked in half along its entire length, it was actually cracked in thirds or approximately 120° pie segments. The appearance of this cracked extrusion after it was cut to facilitate handling is shown in Figure 26. The appearance of the central core and can indicate that the billet had been cracked before extrusion.

Approximately 8.2 feet of tube were produced from the first extrusion. The extrusion was first straightened to within 0.05 inch/foot on a hydraulic bar straightener similar to a large production barrel straightener, sectioned to the approximate final length on an abrasive cutoff wheel, and restraightened in the same equipment to within 0.01 inch/foot. This procedure yielded 4 lengths of

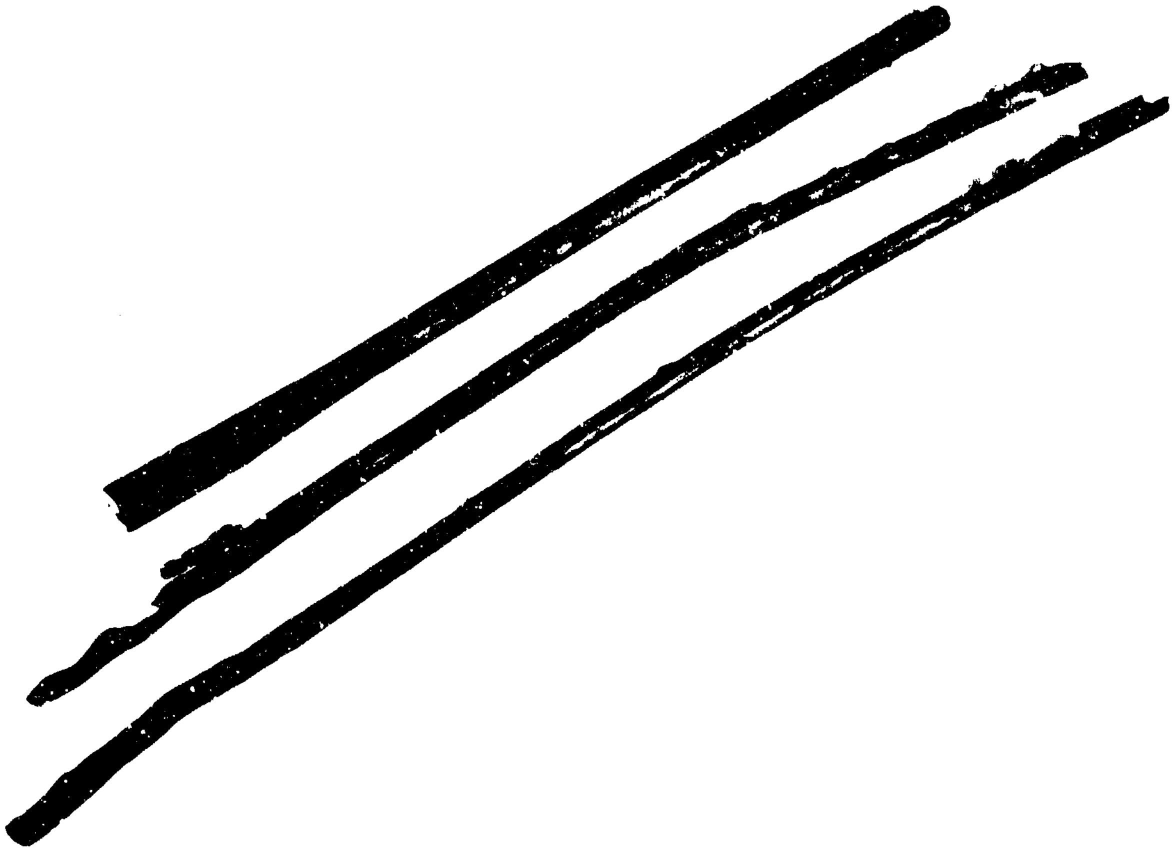


Figure 26. Cracked filled billet extrusion of the cobalt base alloy.

cobalt alloy 23 inches long with the following dimensions: inner diameter of 0.235 ± 0.015 inch and outer diameter of 1.290 ± 0.010 inch. The extruded bars were conventionally gun drilled with a 0.3125 inch diameter gun drill and cylindrically ground on centers to completely remove the can and grind the outer diameter concentric with the centers. The final dimensions of these bars are listed in Table VIII. The actual tube yield from this extrusion was 56 percent.

TABLE VIII

Final Dimensions of Cobalt Alloy Barrel Blanks

Blank No.	Length (inch)	Outer Dia. (inch)	Inner Dia. (inch)	Total Max. Runout (in.) from Center	Hardness R_c
C-1	23.12	1.233 ± 0.002	0.312 ± 0.0005	0.004	54.0 ± .5
C-2	23.06	1.242 ± 0.001	0.3206 ± 0.0006	0.003	54.0 ± .5
C-3	23.21	1.228 ± 0.002	0.3125 ± 0.0002	0.003	54.0 ± .5
C-4	23.12	1.242 ± 0.001	0.3132 ± 0.0006	0.007	54.0 ± .5

The first extrusion was radiographically inspected which provided no defect indications. However, fine radial and random cracks were observed on the ends of all the finished tubes. Dye penetrant inspection of the tubes showed that the cracks were restricted to the tube ends and were very shallow as indicated by a very small amount of bleeding at the edge of the outer diameter. Approximately 0.10 inch was machined off the ends of each blank before a reinspection with die penetrant. This inspection showed the bars to be defect free.

The hardness of R_c54 exhibited by all the bars after extrusion was not entirely unexpected because of the previous process evaluation results. Although preparation of the tubes at this hardness level is not desirable, it was performed to avoid any deleterious effects on the cobalt from thermal cycling and quenching the bi-metallic rod. Because the blanks were finished, heat treatment had to be performed in a protective atmosphere. Before this treatment the blanks were thoroughly cleaned with trichloroethylene. The C. I. Hayes Co., Rhode Island provided the use of their vacuum heat treatment and quench unit to perform the necessary heat treatments completely under a good industrial vacuum. With this unit, the part could be maintained in vacuum and quenched in oil (H-1) directly from the hot zone. Based on the results in Table VII and Figures 17, 18, 21 and 22, the blanks were annealed at 1850°F and 2000°F in vacuum and quenched directly into oil to provide hardnesses of R_c48 ± 1 and 47 ± 1 respectively. These heat treatments were performed by charging the blanks into the vacuum chamber at room temperature, heating to temperature in about 5.5 hours

and holding for 30 minutes before quenching. Because of a slight discoloration of blank C-2 annealed at 2000°F, all of the other blanks were annealed at 1850°F. The blanks appeared to become more lustrous after the 1850°F anneal.

The total indicated runout from the centerline of the blanks increased to 0.060 to 0.080 inch after the vacuum heat treatment and quench. As an added precaution for swaging, all the blanks were straightened to within 0.001 inch/inch using movable vee blocks on an arbor press (similar to conventional barrel straightening procedures). After straightening the blanks were dye penetrant inspected and were found to be defect free. These procedures concluded the barrel blank preparations for swaging.

3.30 Rifling

All rifling was performed at room temperature by swaging in a Cincinnati Millacron Intraform rated at 100 tons. Rifling mandrels were prepared from Carballoy 55B to conform with Part No. 11701204 with nominally constant land and groove diameters in the rifled area for the following conditions:

	Diameter (inch)	
	Land	Groove
1. Finished barrel (mandrel No. 1)	0.2997 ± 0.0001	0.3075 ± 0.0001
2. Barrel prepared for electroplating (mandrel No. 2)	0.3067 ± 0.0002	0.3138 ± 0.0001

The mandrel prints are presented in Figures 27 and 28. Because of relatively long delivery schedules, the mandrels were designed and ordered before extensive swaging had been performed. The mandrel dimensions were selected on the high side of average specifications to allow for bore contraction after machining previously experienced in M-14 (6) process development. Because of many unique features of the mechanical behavior of superalloys and tool steels it was anticipated that fabrication procedures and performance for these alloys will differ from conventional barrel alloys. Therefore, a process evaluation was performed to establish a base line for swaging process design for subsequent full scale fabrication. The results of this process evaluation will be presented first followed by the application of these results, the full scale fabrication.

3.31 Process Evaluation

Process evaluations to establish base line data were performed with the dies and general tooling set up anticipated for use with the full scale barrel fabrication with the exception of guide bushings. Because a variety of blank diameters were used for the evaluations, rigid guide bushings were not used. In these studies, two 6 inch neoprene packed sleeves at the entrance

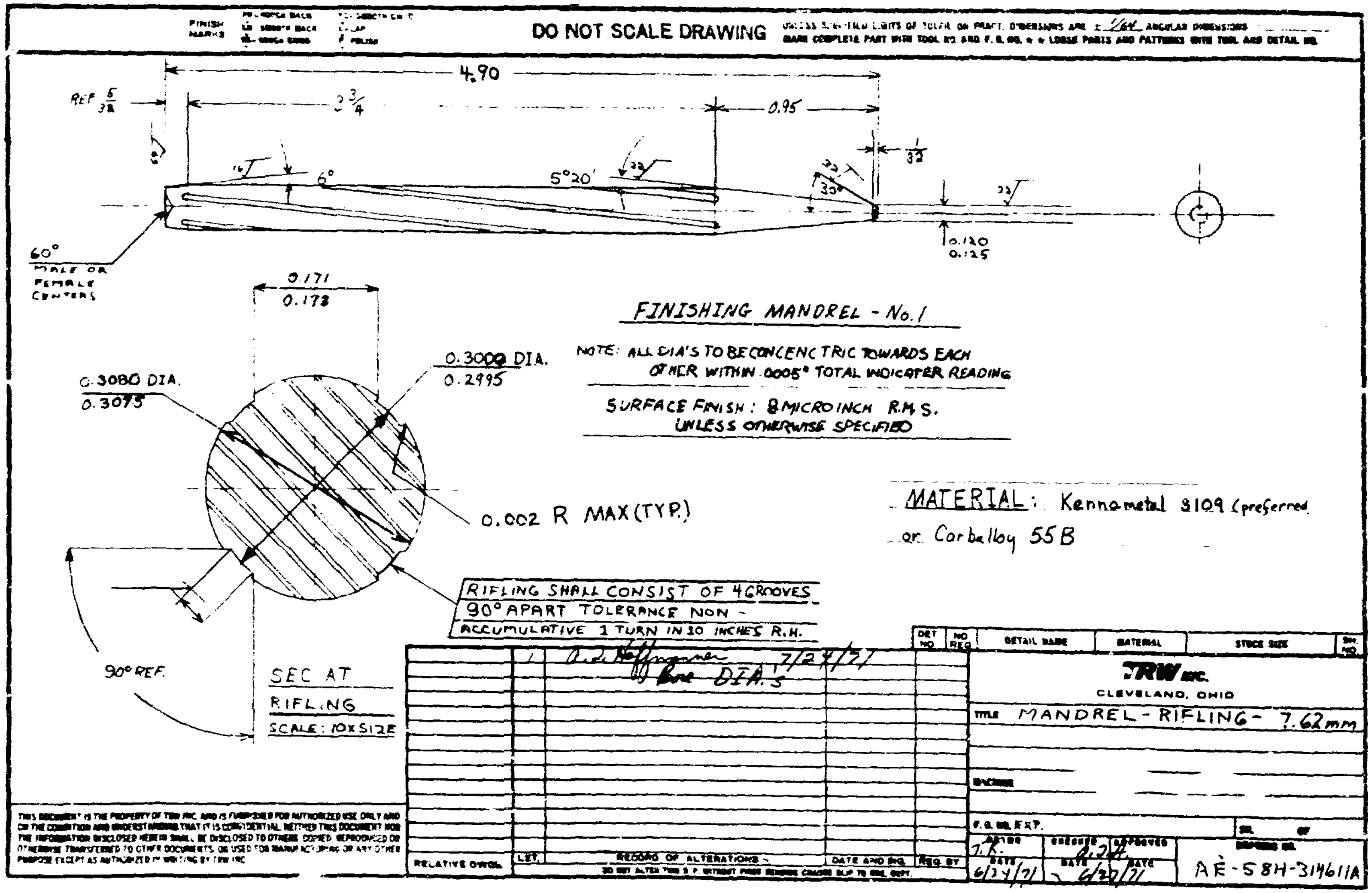


Figure 27. Mandrel No. 1: Finishing mandrel to produce a blank with finished bore dimensions.

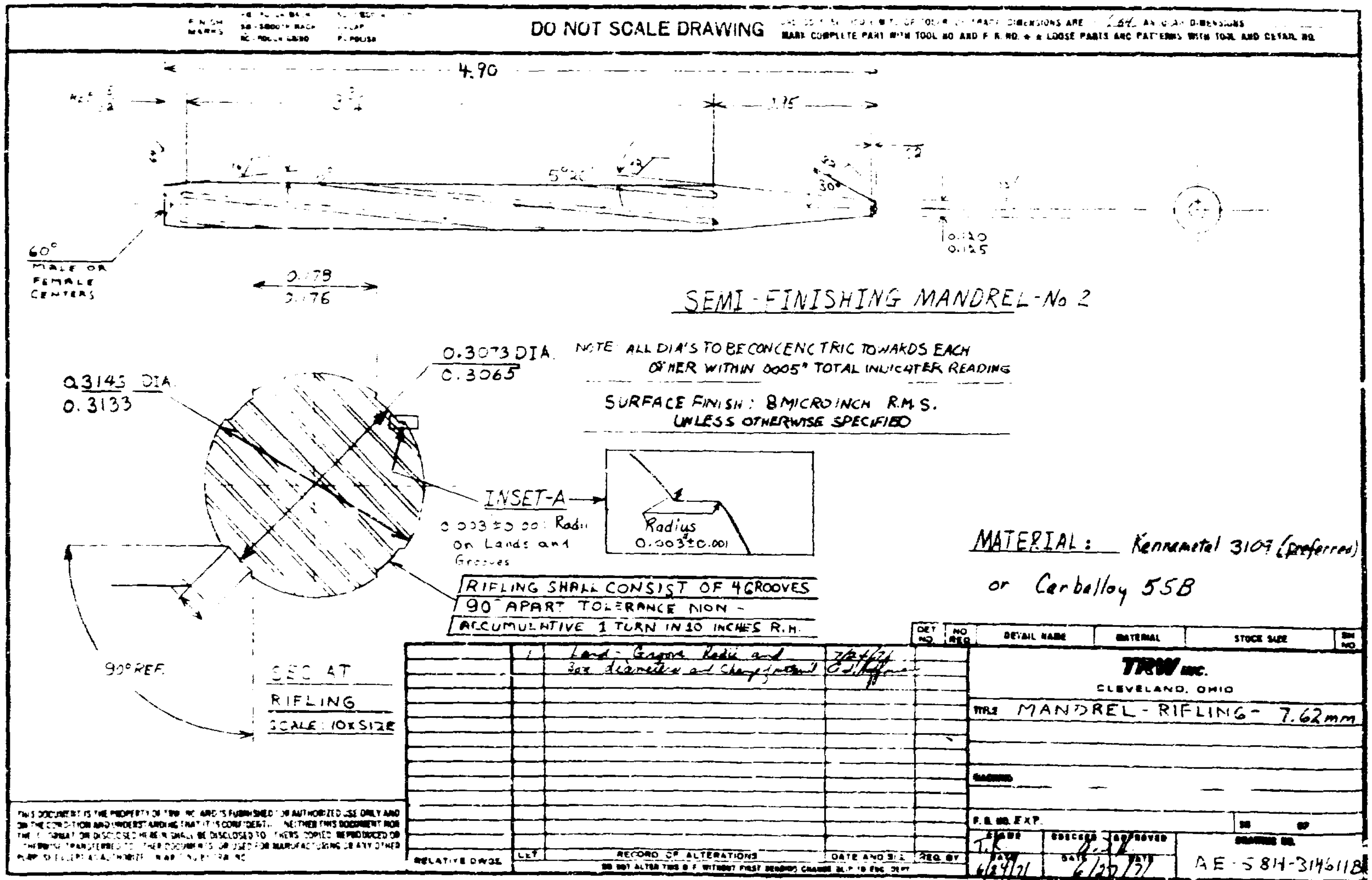


Figure 28. Mandrel No. 2: Semi-finishing mandrel to produce a blank with bore dimensions for subsequent electroplating.

and exit to the dies were used both for guiding and controlling the part rotation. The dies were made of M-2 high speed steel hardened to R_c 65-67 with a 3° entrance angle, a 0.5 inch radius entry to a 0.5 inch land, a 1.305 inch diameter bore, and a 1° exit angle. The feed rate was arbitrarily set at 10 inch/minute. A mixture of 50 percent molybdenum disulfide in a heavy grease was used for mandrel lubrication and was selected on the basis of past experience.

The major unknown factors which affect process design and cost during swaging are minimum reduction to achieve the product, maximum reduction before incipient product degradation, and surface quality as affected by stock preparation and swaging. These factors were investigated in the following process evaluations.

3.311 The Effect of Reduction on Bore Dimensions

Reduction during swaging is a significant economic factor because it determines the starting blank length which affects tube fabrication costs. However, excessive reduction promotes longitudinal cracking which is also enhanced by the concentration of second phase particles. Since the microstructures of Inco 718 and the cobalt alloy are particularly complex, preliminary swaging trials were performed to determine the minimum reductions required for rifling and also the maximum reductions attainable before cracking to evaluate the feasibility of chambering by swaging. These swaging schedules were based on the results of Kalpakjian (7) and Kegg (8) for free and mandrel swaging respectively. Kalpakjian showed that the change of the outer diameter ΔD_o was equal to the change of the wall thickness Δt for swaging to reductions of approximately 30 percent. This equality can be rewritten in terms of ΔD_o, the initial inner and outer diameters, D_i and D_o, respectively, and the change of the inner diameter ΔD_i to provide the relation

$$\Delta D_i = \Delta D_o \left(2\frac{D_i}{D_o}\right) \approx 1.73\Delta D_o \qquad \text{Equation 1}$$

for free swaging of tube. For mandrel swaging, Kegg found that the profile depth d in filling a slot in a mandrel for the most adverse conditions for fill in his experiments (12° die angle) was equal to 0.67 ΔD_o, or for mandrel swaging

$$d = 0.67\ \Delta D_o \ . \qquad \text{Equation 2}$$

In the use of Equations 1 and 2, it should be recognized that overgrind and die angle can affect the relations and that although Kalpakjian and Kegg used a variety of tube sizes, their tubes had thinner walls, i.e., smaller ratios of tube thickness to outer diameter, than the tubes being used for making barrels.

Equations 1 and 2 were evaluated using the following conditions:

1. Sigmoidal or parabolic die with an included die angle varying between 3° to 1° from entrance to exit;

2. Die bore diameter of 1.385 inch corresponding to an overgrind in excess of 10%;

3. Feed rate of 6 inch per minute; and

4. A mandrel made almost identical to the No. 1 design in Figure 27.

Both the small die angle and the relatively large overgrind are known to promote I.D. deformation equivalent to or greater than the conditions used for developing Equations 1 and 2. Under these conditions the following results were obtained:

Blank No.	Initial Dimension (in.) O.D.	Initial Dimension (in.) I.D.	Swaged Dimension (in.) O.D.	Swaged Dimension (in.) I.D.	ΔD_o (inch)	ΔD_i (in.) Observed	ΔD_i (in.) Calculated	D_i (in.) Calculated
1-21	1.2088	0.3333	1.176	0.313	0.0328	0.0203	0.0535*	0.3018
1-22	1.2354	0.3151	1.213	0.306	0.0224	0.0091	0.0129	0.3022

* Calculation based on completely free swaging.

These results show that the greatest disparity between the barrel swaging measurements and the results of Kalpakjian and Kegg occurs during free swaging. In this case there is a factor of 2.5 relating the observed to the predicted. This disparity may have been hidden in Kalpakjian's data at low reductions due to the scatter of his measurements. The cause for this possible disparity in Kalpakjian's data may be associated with partial yielding at the I.D. at low reductions. This possibility was clearly apparent with swaged blanks 1-21 and 1-22 as shown by the concavity of the end surfaces (i.e., the elongation of the tube decreased from the O.D. to the I.D.)

Based on the results for 1-21, a revised Equation 1 can be obtained for free swaging by recognizing that $\Delta D_i/\Delta D_o = 0.0203/0.0328 = 0.62$, or

$$\Delta D_i = 0.62\Delta D_o. \qquad \text{Equation 3}$$

This relation differs from Equation 1 by a factor of nearly 3. The use of Equations 2 and 3 for calculations of D_i for blank I-22 provides $D_I = 0.3042$ inch. This result indicates that Equation 2 provides a 50% overestimate of the diameter reduction.

Subsequent swaging trials were performed with a straight tapered die of 6° included angle, overground to 1.250 inch. This die is not as favorable as the previous design in promoting deformation at the bore, but represents the best conditions for this purpose investigated by Kalpakjian and Kegg. In order to reuse I-22, the bore was reamed to 0.310 inch. The following results were obtained with these new conditions.

6° Die:

Blank No.	Initial Dimension (in.) O.D.	Initial Dimension (in.) I.D.	Swaged Dimension (in.) O.D.	Swaged Dimension (in.) I.D.	ΔD_o (inch)	ΔD_i (in.) Observed	ΔD_i (in.) Calculated	D_i (in.) Calculated
I-21	1.176	0.313	1.133	0.3027	0.043	0.0103	0.0108	0.3022
I-22	1.213	0.310	1.174	0.3021	0.039	0.0079	0.0079	0.3022

The calculated results were obtained from the initial dimensions and the die exit diameter with Equation 3 and a modification of Equation 2 based on the initial swaging results. This modification provides the relation:

$$d = 0.33\Delta D_o = 2\Delta D_i,$$

therefore,

$$\Delta D_i = 0.135\Delta D_o \qquad \text{Equation 4}$$

during mandrel swaging.

The validity of Equations 3 and 4 should not be considered as established based on the experimental findings. Not only are the experimental results too few, but if partial yielding is a significant factor, the relations between ΔD_o and ΔD_I will show a dependence on reduction per pass as well as on total reduction. Equation 4 and the results leading to its development clearly demonstrated that significant reductions are required to form the rifling. This equation showed that the outer diameter was reduced 7.5 times faster than the inner diameter and established that a diameter reduction of at least 0.059 inch was required to form the rifling.

3.312 The Effect of Reduction on the Microstructure of Swaged Blanks

The effect of reduction on the microstructure of the swaged blanks was investigated for Inco 718 and Vasco M-A. In general, the deformation was most severe along the bore surface at both the land and groove areas. However, the area about the land-groove step appeared slightly more disturbed than elsewhere along the bore. The very intense deformation at both the land and groove areas of blank I-22 is shown in Figure 29 after an outer diameter reduction of only 0.039 inch. Figures 30* and 31* show similar cross sections of blanks M-4 and I-10 given total diameter reductions of .060 and 0.074 inch respectively. The deformation along the lands and grooves appeared more severe for the Inco 718 blanks I-10 and I-22 than for the Vasco M-A blank M-4. Since all three blanks were prepared under identical conditions, the localization of the deformation to the bore surface may be dependent on the material, and not a general observation. The microstructure of Inconel 718 is much more complex than Vasco M-A, which has relatively few second phase particles and does not exhibit the strong mechanical texturing typical of wrought nickel-base superalloys.

The severely deformed zone about the bore is about 0.001 inch deep. This zone could easily be removed by electropolishing before chromium plating the bore. However, because the effect of this structure on structural integrity at the bore surface is not known, it was decided to swage the rifling with the minimum necessary reduction. This single reduction was taken to be in the range of 10 percent in excess of the total anticipated from Equation 4. It was assumed that the localization of the deformation was produced by contact with the mandrel. Although a shear or plastic torsional strain is known to arise from swaging (7), this shear appears to be relatively uniformly distributed throughout the cross section during free sinking. This observation appears to be substantiated by the similarity of the microstructures at the outer diameter of the blank and a few thousandths of an inch away from the bore surface. Therefore, it would appear that the effect of free sinking on microstructural rotation should be similar across the swaged tube cross section.

3.313 The Effect of Reduction Over a Mandrel on Bore Surface Finish

The part print required a bore surface finish of 32 microinch. The swaged blanks during process evaluation and preliminary fabrication trials were evaluated to determine how this finish could be achieved and also the magnitudes of the waviness and profile at the bore surfaces. It was found that if any rifling was swaged into the blanks the surface finish was at least less than 25 microinch AA and depended most on the method of tube fabrication before swaging. Gun drilling produces circumferential tool marks which are smoothed, but certainly not eliminated by swaging as shown in Figure 32 for blank I-10. The visual appearance of this bore indicates a rather poor quality surface. However, the profilometer trace in Figure 33 taken over this same segment shows the surface to be of very high quality with a surface finish of 18 microinch AA and a waviness amplitude of 200×10^{-6} inch. This surface

* There is significant relief along the bore particularly on the land at the land-groove step. This relief was difficult to avoid during polishing.

Figure 29. Photomicrograph of land-groove area of swaged blank I-22. 500X.

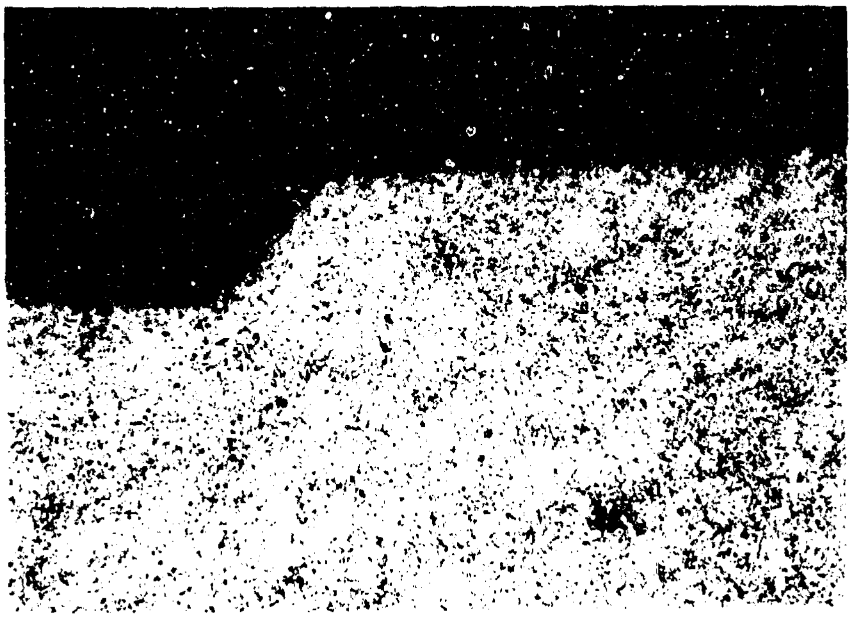


Figure 30. Photomicrograph of land-groove area of swaged

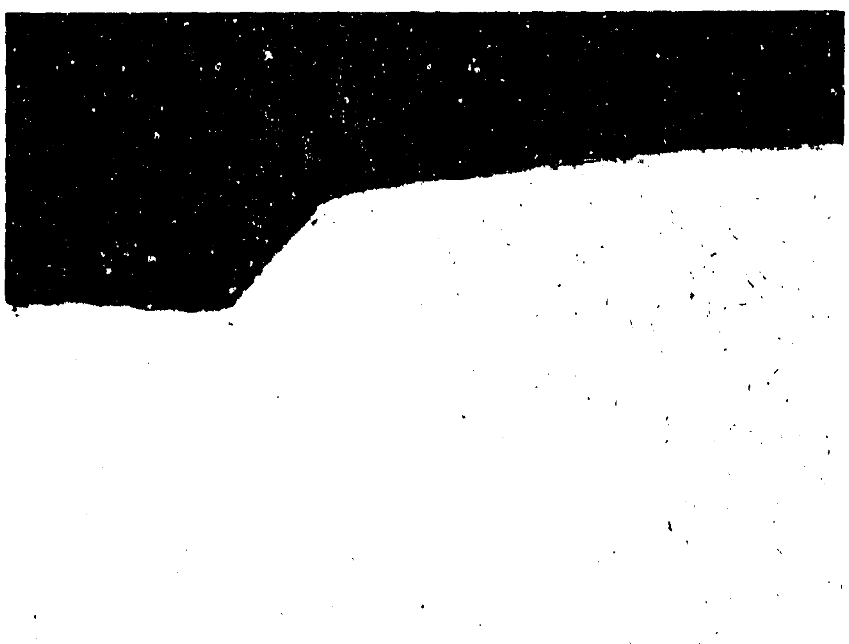


Figure 31. Photomicrograph of land-groove area of swaged blank I-9. 250X.

Figure 32. Macrograph of Inco 718 gun drilled and rifled blank I-10. 2.3X.

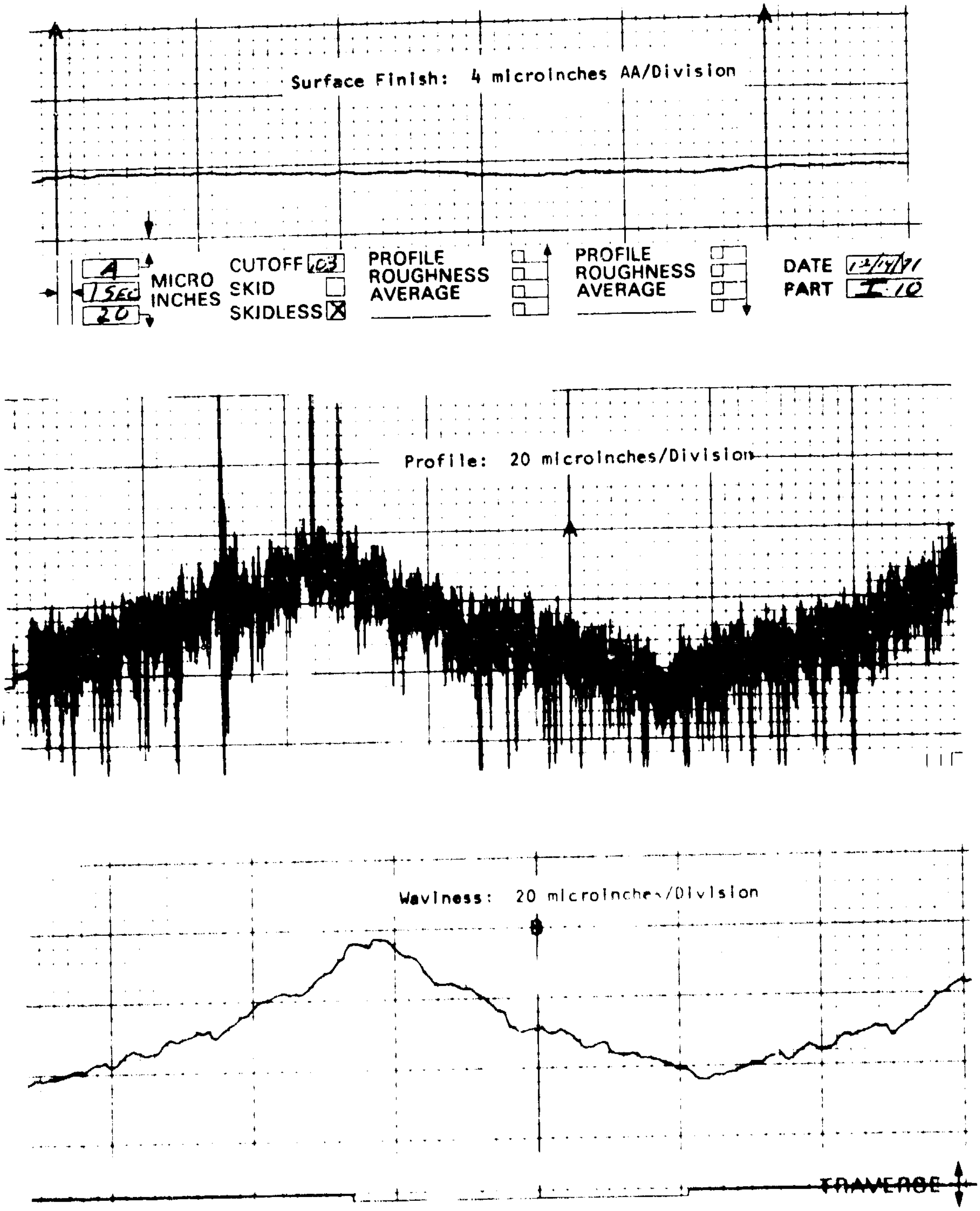


Figure 33. Profilometer traces showing profile, surface finish and waviness on gun drilled and swaged blank I-10.

quality was indicated by sighting through the bore which appeared very bright and lustrous when compared with the bores of commercial and military weapons. The prominance of the tool marks in Figure 32 appeared to have resulted from entrapment of a small amount of mandrel lubricant in the tool marks. The material between the tool marks was brightly burnished by riding over the mandrel. Therefore, the tool marks appear very prominent because of the contrast from the adjacent highly polished material. A less viscous and less efficient lubricant would have produced a brighter but more burnished surface at the expense of smearing and/or tearing of surface material. The flatness or lack of waviness of the swaged surface is indicated by the very low waviness measurements from these surfaces.

Measurements of surface finish and waviness performed before and after swaging are shown in Table IX for gun drilled and ECM stem drilled blanks at various initial values of surface finish. The significant feature of these results was the similarity of the profilometer measurements after swaging. Although the profilometer measurements on the ECM drilled blank I-3 and the gun drilled blank I-10 are similar before and after swaging, visual observation indicated a difference which can be observed by comparing Figures 32 and 34. The bore segment from I-3 shown in Figure 34 appears to possess a better surface finish than I-10. However, as previously discussed, I-10 has regularly spaced very shallow tool marks on a brightly polished surface, whereas I-3 has randomly spaced very shallow depressions from small, localized random variations of electrochemical machining.

3.314 The Effect of Machining the Outer Diameter on Final Bore Dimensions

The effect of machining the outer diameter of the blanks after swaging was investigated with the half length blanks I-21 and I-22 after area reductions of 12.5 and 9.7 percent respectively. These reductions corresponded to the maximum and minimum anticipated for barrel fabrication. The blanks were ground on centers under low stress conditions (2000 SFM wheel speed, 0.0005 inch per pass, soft H grade wheel, and with a strong coolant flood) to minimize alteration of the residual stress pattern produced by swaging. The diameters were reduced in 6 equal operations in which 0.100 inch was removed per operation. After each operation the bores were measured at two positions 2.000 inch and 4.000 inch from the same end with calibrated precision bore gauges with a sensitivity of 0.000025 inch. No change of the bore dimensions was noted until after the third operation where a contraction of 0.00004 to 0.00006 inch was noted for both blanks. After the total 0.60 inch stock removal contractions of 0.00008 $\pm$ 0.00002 inch were measured. The contractions were felt to be insignificant and, therefore, no further consideration was given specifically to the change of bore dimensions as affected by machining the outer diameter.

The deduction that bore ocntractions were insignificant in this evaluation should not be generally applied. Process evaluation studies on M-14 (6) after 48 percent reductions by swaging showed bore contractions in the range of 0.0003 to 0.001 inch. Therefore, the change of bore dimensions after machining will depend, in general, on the reduction, tooling geometry and probably the barrel material. It will be shown that springback immediately after swaging was not particuiarly significant.

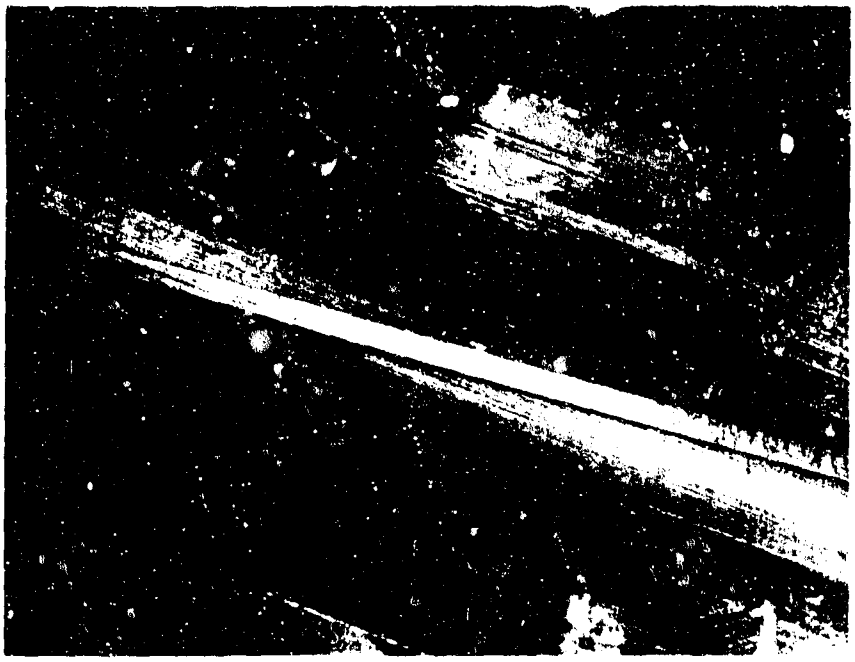


Figure 34. Macrograph of the swaged bore surface of ECM stem drilled blank I-3. 2.3X.

TABLE IX

Profilometer Measurements Before and After Swaging

Blank No.	Measurement Before Swaging (inchx10^{-6}) Surface Finish (AA)	Waviness Amplitude	Measurement After Swaging (inchx10^{-6}) Surface Finish (AA)	Waviness Amplitude
I-3*	60	700	20	180
I-10	65	650	19	205
M-12	135	450	12	80

* ECM stem drilled blank

3.315 The Maximum Reduction Attainable by Swaging Inconel 718, Vasco M-A and the Cobalt base Alloy

The maximum reduciton attainable is an important economic factor once it has been established that the product can be swaged. Since the volume of the blank is determined by the product size, heavy reductions permit the use of short blanks of large diameters with reduced tube preparation costs. Furthermore, the capability of material to withstand large reductions permits simultaneous swaging of the chamber and rifling. Since the maximum chamber diameter is 0.478 inch, Equation 3 requires that a free reduction of the outer diameter of 0.28 inch is required for the inner diameter to become 0.308 inch. From Equation 4, an additional 0.059 inch reduction of the outer diameter is required to achieve the proper bore dimensions. Therefore, the starting blank diameter for simultaneous swaging of the chamber and rifling would be determined by the following conditions:

1.	Final rifled tube dimensions:	1.200 inch + 0.000/-0.016 inch
2.	Free reduction from chamber dimensions to mandrel:	0.280 inch (from Equation 3)
3.	Swaging the rifling over the mandrel:	0.059 inch (from Equation 4)
	Minimum starting blank diameter:	1.539 inch.

To test the feasibility of swaging both the chamber and rifling in one operation, blanks were parepared from Inconel 718 at two hardness levels R_c36 and 45 and Vasco M-A at one hardness, R_c36. The initial dimensions of these blanks were nominally 1.250 inch outer diameter and either 0.316 or 0.392 inch inner diameter. After the first reduction of the outer diameter,which was nominally 0.065 inch, each successive reduction was nominally 0.080 inch. After each reduction beyond the first, the blanks were examined, their inner and outer diameters measured, and a 1.0 inch length was removed for closer examination before the next sequence was begun. The results of these observations are listed in Table X which show that these alloys are capable of very large reductions by free sinking or swaging without a mandrel. Although simultaneous rifling and swaging of Inco 718 at R_c45 would be a marginal procedure, all of the blanks listed in Table X sustained sufficient reductions to accomplish this objective.

The initial reduction of hardness observed during the swaging of these blanks (see Table X) has been observed by others (9) with conventional steels for commercial weapons and has been attributed to the Bauschinger effect. This latter deduction is erroneous and unfortunate because the hardness reductions involve factors which could affect performance if the source of these reductions are not understood. The initial reductions of hardness are caused by the competing effects of work hardening and residual stress on the load required to produce the hardness impression. The state of stress affects the impression load through a yield criterion involving the multiaxial state of

TABLE X

Results for Determination of Maximum Reduction by Free Sinking

Blank No.	Pass No.	Outer Diameter(inch)	Inner Diameter(inch)	Hardness (Rc)	Remarks
I-8	0	1.267	0.316	36	
	1	1.202	N.M.*	N.M.*	
	2	1.104	0.185	37	
	3	0.938	0.161	36	No cracks
S-7S	0	1.212	0.4135	45	
	1	1.122	0.319	42	
	2	1.056	0.266	41.5	Small radial end crack
	3	0.946	0.205	42.5	Cracked radially into 3 equal pie-shaped segments
S-7L	0	1.219	0.4135	45	
	1	1.125	0.315	42	
	2	1.058	0.261	42	
	3	0.947	0.207	42	No cracks
M-3	0	1.2495	0.316	36	
	1	1.182	0.259	33.5	
	2	1.124	0.229	32	
	3	1.050	0.187	32	
	4	0.943	0.147	28	
	5	0.823	0.101	37	No cracks

* Not measured.

stress caused by the indenter and the state of residual stress in the material about the impression. Continued reductions will eventually produce a steady state residual stress gradient, but work hardening will result in a continuous increase of hardness which will not become apparent until the steady state residual stress gradient has been established. Therefore, a hardness minimum would be expected if the effect of residual stress on the apparent hardness was greater than work hardening during the initial reductions. This minimum is demonstrated by the measurements for blank numbers M-3 and S-7S in Table X.

The existence of residual stress in a wrought product, in general, necessitates a gradient of residual stress to achieve stress equilibrium. Because of the state of residual stress at any particular position in the product will be multiaxial, the particular value of the hardness measurements will depend both on the direction and position of the impression. Sectioning will also affect the residual stress. However, if residual stress is the major contributing factor to the hardness reductions, hardness measurements should change significantly with the radial position of the measurement on a cross section of the swaged blank and stress relief treatments shou produce noticeable hardness increases. These deductions are amply supported by the results in Table XI made after various reductions at different radial positions from the bore, on the outer diameter before and after heating at 900°F and 1100°F, a relatively low stress relieving temperature for these alloys, for 1.5 hours.

The results in Tables X and XI demonstrate the need for stress relieving treatments to achieve both dimensional stability and barrel performance independent of the state of residual stress. The measurements made on these barrels indicate that the states of stress are compressive at the bore and tensile at the outer diameter. However, the actual magnitudes of the stresses will determine whether the residual stress is beneficial or detrimental. If the circumferential component of the residual stress at the outer diameter is nearly equal to the yield stress, the bore dimensions could be metastable. Subsequent firing could then produce bore growth.

Results for swaging of the cobalt base alloy were minimal because cracking followed even minimal reductions required to form the rifling. During swaging, radial cracks generated through the entire wall thickness from the base of the step at the land-groove junction.

3.32 Rifling by Swaging Full Size Rifle Blanks

Rifling by swaging was attempted under a variety of conditions to determine the feasibility of various fabrication routes which would affect the overall cost and quality of the barrels. The major problems encountered were the breakage of mandrels and brinneling or deforming of the dies. All mandrel breakage occurred with the Inconel 718 blanks and was always preceded by small amounts of galling on the mandrel. This galling appeared to form on the region of the mandrel near the land exit just before the die relief where the die and blank no longer contact. The galled areas appeared predominantly on the grooves

TABLE XI

Hardnesses of Swaged Segments

Specimen No.	Specimen Condition	Radial Position of Hardness Measurement on Segment Cross Section: Center	Mid-Thickness	Near Outer Dia.	Hardness Taken on Outer Dia.
M-3 (5th reduction)	As swaged	$R_c 38$	$R_c 36$	$R_c 46$	$R_c 37 \pm 0.5$
S7S (2nd reduction)	As swaged	$R_c 35$	$R_c 41$	$R_c 41.5$	$R_c 42.8 \pm 0.2$
S7S (3rd reduction)	After 1-1/2 hr. at 900°F	$R_c 47$	$R_c 46$	$R_c 46$	$R_c 46 \pm 2.0$
	After 1-1/2 hr. at 1100°F	$R_c 47$	$R_c 47.5$	$R_c 48$	$R_c 47.5 \pm 1.0$
I-8 (2nd reduction)	After 1-1/2 hr. at 900°F	$R_c 38$	$R_c 37$	$R_c 39$	$R_c 40 \pm 1.0$
	After 1-1/2 hr. at 1100°F	$R_c 42\text{-}1/2$	$R_c 42$	$R_c 44$	$R_c 46 \pm 0.5$
M-3 (4th reduction)	After 1-1/2 hr. at 900°F	$R_c 35.5$	$R_c 35$	$R_c 35$	$R_c 33.5 \pm 1.0$
	After 1-1/2 hr. at 1100°F	$R_c 35$	$R_c 35.5$	$R_c 35.5$	$R_c 33 \pm 1.0$

in the mandrels (rifle lands). The galled areas appeared as bright spots on the mandrel usually less than 0.070 inch long and 0.040 inch wide. Occasionally more than one galled area was observed. The galled areas could be nearly completely removed with some diligence by selectively polishing these areas with 2 micron diamond paste applied with a small wood stick. With continued polishing the size of the galled spot could be observed to decrease at the same time the luster of the mandrel in the polished area increased. Observations of this polished region at a magnification of 30X revealed no noticeable removal of carbide and, before the mandrel was reused, no apparent galled metal. However, the luster of the surrounding carbide could have impaired resolution of the last traces of galled metal. This latter deduction is based on the finding that once galling began with Inco 718 it continued even after polishing. However, if the galling was removed by polishing Vasco M-A bars could be run without any difficulties or additional galling. All cases of mandrel breakage occurred with Inco 718 and galling, although relatively light, was observed. Galling during swaging of Inco 718 occurred at all hardness levels, but in a random or occasional manner. The frequency of occurrence was highest for the blanks at R_c45 and was observed in 4 of the 5 trials. One of the trials (H-1) resulted in breakage of the mandrel support rod; the next trial on a blank (I-14) at R_c36 resulted in mandrel breakage; the next trial (I-15) with a new mandrel (No. 1 mandrel) resulted in a small amount of pickup; and the next three (I-16, I-17 and I-18) all produced galling. This mandrel was repaired by removing the entire end (0.9 inch) from the point of galling initiation. After this mandrel was ground and polished on the cut end it was replaced and used for swaging I-6. The general swaging results and problems are reviewed in Table XII for all of the full length blanks swaged.

The blanks shown in Table XII were swaged using two differnet guiding assemblies before and after the die. The first assembly used two 6 inch long tubes 2 inches in diameter which were packed with a neoprene tube to provide an expandable opening from about 0.75 to 1.3 inch diameter. One of these tubes were located before and the other after the swaging dies to reduce the part rotation and to provide rigid radial guiding of the part at the entrance and exit of the dies. An addition was made to this guiding assembly to provide improved guiding. This addition involved two bronze tubes or bushings 1.200 + 0.001 inch inner diameter and 7.00 inch long. One bushing was placed in a rigid fixture aligned along the centerline of the swage immediately before the neoprene filled tube at the die entrance. Therefore, the gun tube would be guided over at least 13 inches on the entrance side of the die. The other bronze bushing was placed on the end of the accepter rod assembly to guide the swaged blank during die exit. The accepter rod of 1.00 inch diameter was used to apply a back pressure on the part during swaging to achieve a constant feed rate and feed force. The acceptor rod is fed into the dies before swaging and subsequently maintain a constant axial force of 200 pounds on the part as the feed rod forces the acceptor to retract during forming. The acceptor rod retracts into a 2.00 inch diameter tube. However, considerable whipping of the swaged blank and acceptor rod could occur during the final stages of swaging. The effect of this whipping appeared sufficient to bend the tubes near completion of swaging.

TABLE XII

Swaging Results on Full Size Blanks

Blank No.	Diameter Dimensions (inch) Initial I.D.	Initial O.D.	Final I.D.	Final O.D.	Total Indicated Runout From Center	Nominal Hardness R_c	Remarks
I-1	0.316	1.2665	0.3069	1.1915	0.013	36	
I-2							Used for ECM process evaluation
I-3*	0.3282		0.308	1.190	0.006	36	ECM drilled
I-4	0.3282		0.3085	1.214	0.076	(33.6)	Galling, mandrel broke
I-5	0.3282		0.3070	1.184	0.0152	22	
I-6*	0.3202	1.2612	0.3071	1.1945		36	ECM drilled
I-7	0.3161	1.2475	0.3089	1.1905	0.020	22	
I-8	0.3160	1.2670		1.188		36	Gun drill broke used for process evaluation
I-9	0.3164	1.2685	0.3070	1.188	0.014	36	
I-10	0.3162	1.2685	0.3069	1.1940	0.0235	36	
I-11*	0.3164	1.2665	0.3073	1.1940	0.011	36	
I-12*	0.3163	1.2675	0.3069	1.1925	0.010	36	
I-13*	0.3167	1.2755	0.3069	1.1947	0.012	36	
I-14*	0.3162	1.2750	-	-	-	36	Mandrel broke
I-15*	0.3162	1.2755	0.3017	1.2000	0.018	45	
I-16*	0.3165	1.2760	0.3017	1.2000	0.0135	45	
I-17*	0.3172	1.2755	0.3017	1.1997	0.035	45	
I-18*	0.3170	1.2750	0.3017	1.1997	0.0085	45	
H-1	0.3162	1.2500			-	45	Mandrel broke
M-1*	0.3159	1.2530	0.3075	0.0135	0.039	36	
M-2					-	55	Used for ECM evaluation
M-3	0.3161	1.2510			-	36	Used for process evaluation

TABLE XII (Continued)

Swaging Results on Full Size Blanks

Blank No.	Diameter Dimensions (Inch) Initial I.D.	Initial O.D.	Final I.D.	Final O.D.	Total Indicated Runout From Center	Nominal Hardness R_c	Remarks
M-4	0.3158	1.2520	0.3075	1.1985	0.039	36	
M-5	0.3160	1.2515	0.3115	1.2160	0.0685	36	Used for ECM chambering
M-6	0.3157	1.2515	0.3074	1.1995	0.011	36	
M-7*	0.3161	1.2525	0.3071	1.190	0.013	36	
M-8*	0.3155	1.2530	0.3071	1.190	0.0205	36	
M-9*	0.3158	1.2530	0.3073	1.1895	0.008	36	
M-10*	0.3152	1.2530	0.3072	1.1880	0.011	36	
M-11*	0.3157	1.2530	0.3070	1.1855	0.005	36	
M-12*	0.3150	1.2525	0.3071	1.1875	0.013	36	
C-1*	0.3116	1.2350	-				Cracked during swaging
C-2*	0.3212	1.2430	-				" "

* Special guiding tubes were used during swaging of these blanks.

Therefore, the second bronze bushing was placed on the end of the 2.00 inch diameter acceptor tube and then against the neoprene filled guide to provide 13 inches of rigid guiding upon exit of the blank from the dies. The blank numbers marked with an asterisk in Table XII were swaged using this latter assembly. The use of this additional guiding did reduce the runout (see Table II) of the swaged blanks and appeared to reduce the runout to below that of the starting blanks.

The improved guiding indicated that the swage could accommodate tubes of relatively large runout and might produce a total runout less than the as-drilled blank. To test this hypothesis, blanks I-13, I-14, I-16 and I-17 were drilled eccentrically to produce approximate total indicated runouts of 0.030 and 0.060 inch. A comparison of the results in Table II and Table XII indicated that the improved guiding can result in a total indicated runout which is less than or equal to the runout of the as-drilled blanks.

The results in Table XII confirm the predictions of Equations 3 and 4. The occasional oversized blanks which were swaged resulted primarily during initial setup. A portion of the problems in initial setup of the swage resulted from the lack of the process evaluation results. Based on published swaging results (7,8) which were not applicable to barrel fabrication, gun drills of standard diameters (0.3281 and 0.3125) were initially purchased. The first blanks in this program were drilled to the larger diameter and subsequently could only be swaged to the proper bore size with reductions below the minimum specified outer diameter. This problem was subsequently averted by acquiring smaller drills (0.316 inch) and using only the larger diameter blanks with 0.328 inch diameter drills.

3.40 Chambering

Chambering was the last step in barrel fabrication and involved several sequential operations. The need for the several chambering operations arose from the required dimensional accuracy, large length of bearing surface on the chamber reamer, and the necessary good surface finish. Because of the amount of bearing surface during chamber reaming, tool loads were high. For this reason chamber reaming has usually been performed by generating the final chamber form in 0.010 to 0.020 inch increments of length and diameter. The final surface was then obtained using a crush formed felt cylinder charged with polishing abrasive. Polishing is basically a smoothing operation at extremely small metal removal rates with virtually no form producing capability. Therefore, if a tool edge breaks down in a small localized area and scores the chamber, the barrel is lost because polishing cannot remove deep tool marks or scores. The basic problem with this procedure for producing high strength steel and particularly superalloy barrels is the short life of high speed steel and carbide chambering tools. Preliminary results with M-4 high speed steel 4-fluted chamber reamers (R_c65/67) on Inco 718 at R_c36 taking a 0.004 inch average depth of cut showed a maximum life of three chambers before

regrinding was required. Although a good quality C-2 grade carbide tool appeared more applicable for this operation, our experience has shown that for critical form cutting operations on superalloys carbide tools can be troublesome because of sporadic localized chipping. Although the life of carbide tools exceed the life of high speed steel by usually a factor of 3 to 6 for this type of operation, high speed steel tools exhibit general edge breakdown which can be discerned visually and by audible chatter before severe degradation of the form surface. For this reason, chamber roughing with carbide tools would be preferred. Finishing with relatively light depths of cuts, less than 0.004 inch per tooth, could be performed with either carbide or high speed steel. However, carbide tools would require careful observation in this operation.

ECM chambering was evaluated as a potentially advantageous alternative to conventional metal cutting and polishing procedures for chambering. With this procedure the problems with tool wear and breakdown can be averted. Preliminary evaluations were performed on gun drilled (0.316 inch diameter bore) tubes with the following 4 operations:

1. Rough Reaming

   a. Tool Geometry: A 0.432 inch diameter cobalt-high speed steel drill was ground on a tool and cutter grinder using a diamond wheel to produce a 0.50 inch long pilot 0.3150 ± 0.0005 inch diameter and a 20° ($40^\circ \pm 0.1^\circ$) neck area extending from the pilot diameter to the full diameter of the drill flutes.

   b. Machining: The full diameter of the tool (distance from breech to neck) was fed (0.07 inch/min.) into the blank (bore rotation of 50 SFM) a distance of 1.375-0.005 inch.

2. Core Drilling - Breech Chamfering

   a. Tool Geometry: A 0.447-0.002 inch four fluted core drill with an 80° included nose angle was used for this operation. The diameter of this drill expands along 45° 0.640 inches from the nose.

   b. Machining: The core drill was fed 0.656-.010 inch into the breech under conditions similar to rough reaming. This operation produced the 45° breech chamfer and a $0.003 + 0.001$ inch circumferential overcut 0.656 inside the chamber. This overcut or step was performed intentionally on the gun drilled blanks to determine the potential for ECM to remove deep tool marks.

3. Semi-Finish Reaming

a. Tool geometry: A four fluted full form reamer 0.020 inch under finished dimensions was used for semi-finishing up to the small 40° shoulder (80° included angle) at the front of the chamber neck. This reamer produced a 40° shoulder at the front of the neck of 0.330 ± 0.001 inch diameter, the 20° angle on the throat, the diameter of 0.435 ± 0.001 inch at the base of the throat, the 0.013 inch/inch included taper along the chamber body, and the final diameter of 0.453 ± 0.001 inch at the base of the breech chamfer.

b. Machining: The machining conditions for this operation were similar to the preceding. The total feeding length of this tool was 1.881 inch, the distance of the end of the throat from the breech. The diameter of this tool at the overcut produced by the core drill was not sufficient to remove this overcut which resulted in a remaining step of 0.003 + 0.001 inch.

4. ECM Finish Chambering and Polishing

a. Tool design: ECM chambering and polishing to 10 to 15 microinch AA could be produced in one operation with the tooling shown in Figure 35, the blueprint, and Figures 36 and 37 which are photographs of the electrode and fixtures of the assembly prepared for operation respectively. The electrode was machined from stress relieved Ampcalloy 97, 0.024 inch smaller than the semi-finished chamber corresponding to an initial radial cathode-anode gap of 0.012 inch. This electrode was designed 0.054 inch under the finished chamber size. The electrode and barrel guides and electrolyte mixing chamber assembly were constructed as a unit from G-10 epoxy laminate. This material was selected based on past experience and its known strength, dimensional stability and resistance to absorption of moisture. The surfaces of this block bearing against the electrode and barrel were accurately machined and finished to provide guiding surfaces for the barrel blank and electrode. For production application of this unit stainless steel sleeves with "O" ring seals would be fit into these holes. However, for the limited use of this unit, the guiding and sealing was excellent. It was found that the internal guide on the end of the electrode was not necessary and it was not used in these evaluations.

b. Chambering: ECM chambering was performed using the approximate setup shown in Figure 37. This setup has been partially opened to better demonstrate the assembly. The barrel blank has been backed approximately 2.5 inches and the mandrel has been extended approximately 0.5 inch from its operating position. In practice, the mandrel was accurately located to within ± 0.0005 inch from the shoulder of the barrel guiding surface in the guide and mixing

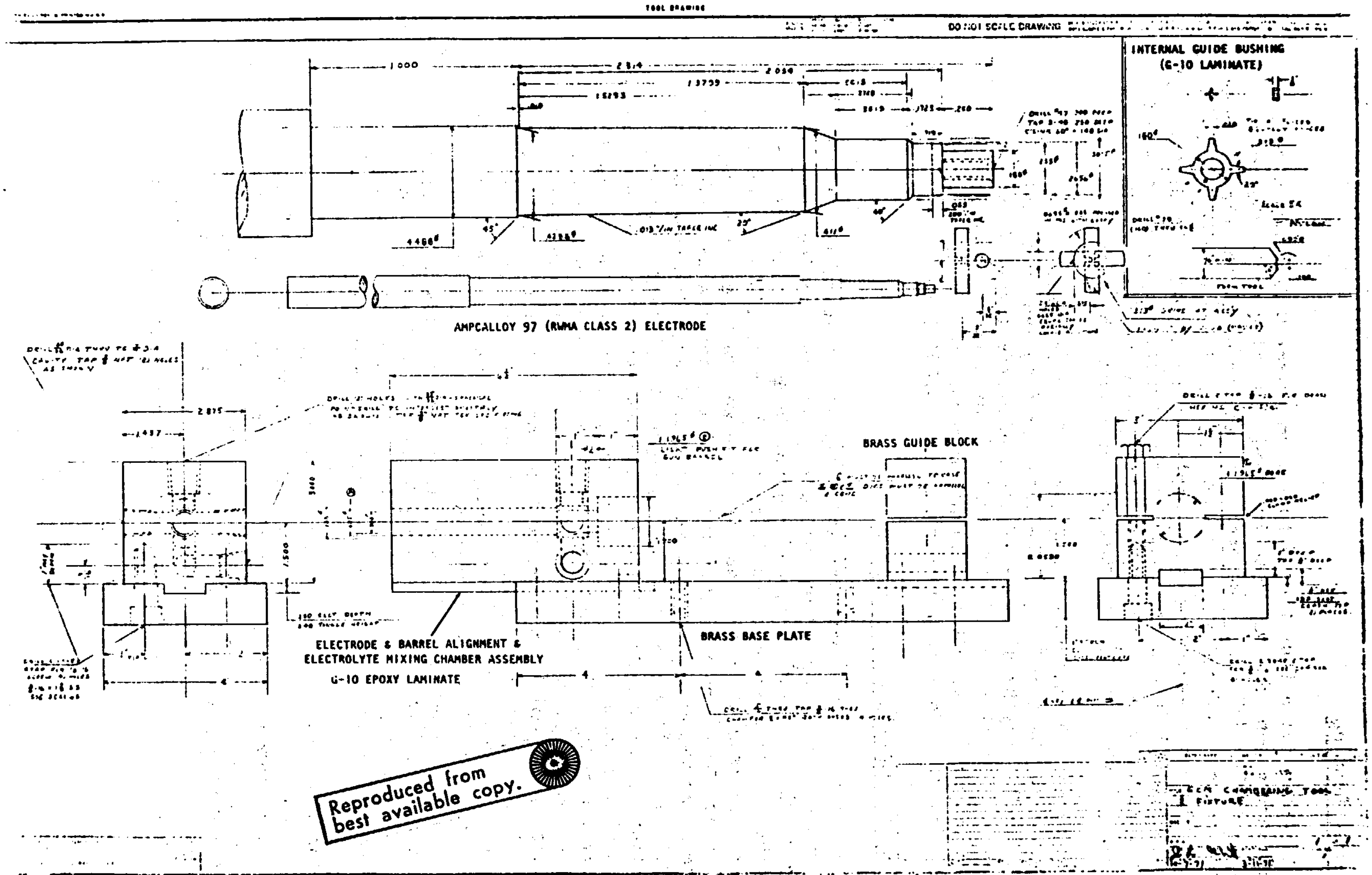


Figure 35. Photograph of blueprint showing ECM chambering tools and fixtures.

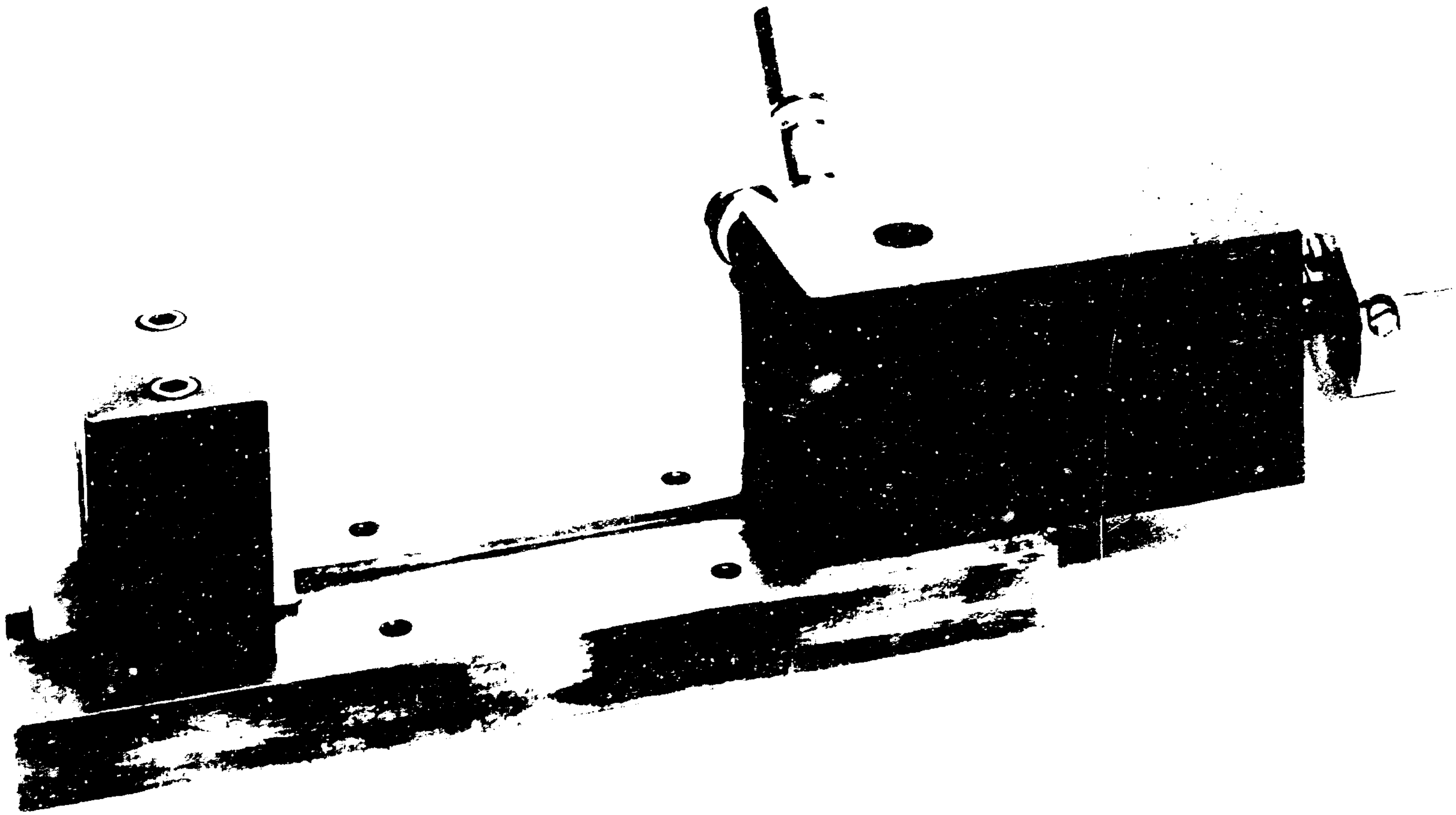


Figure 36. ECM chambering fixture and electrode.

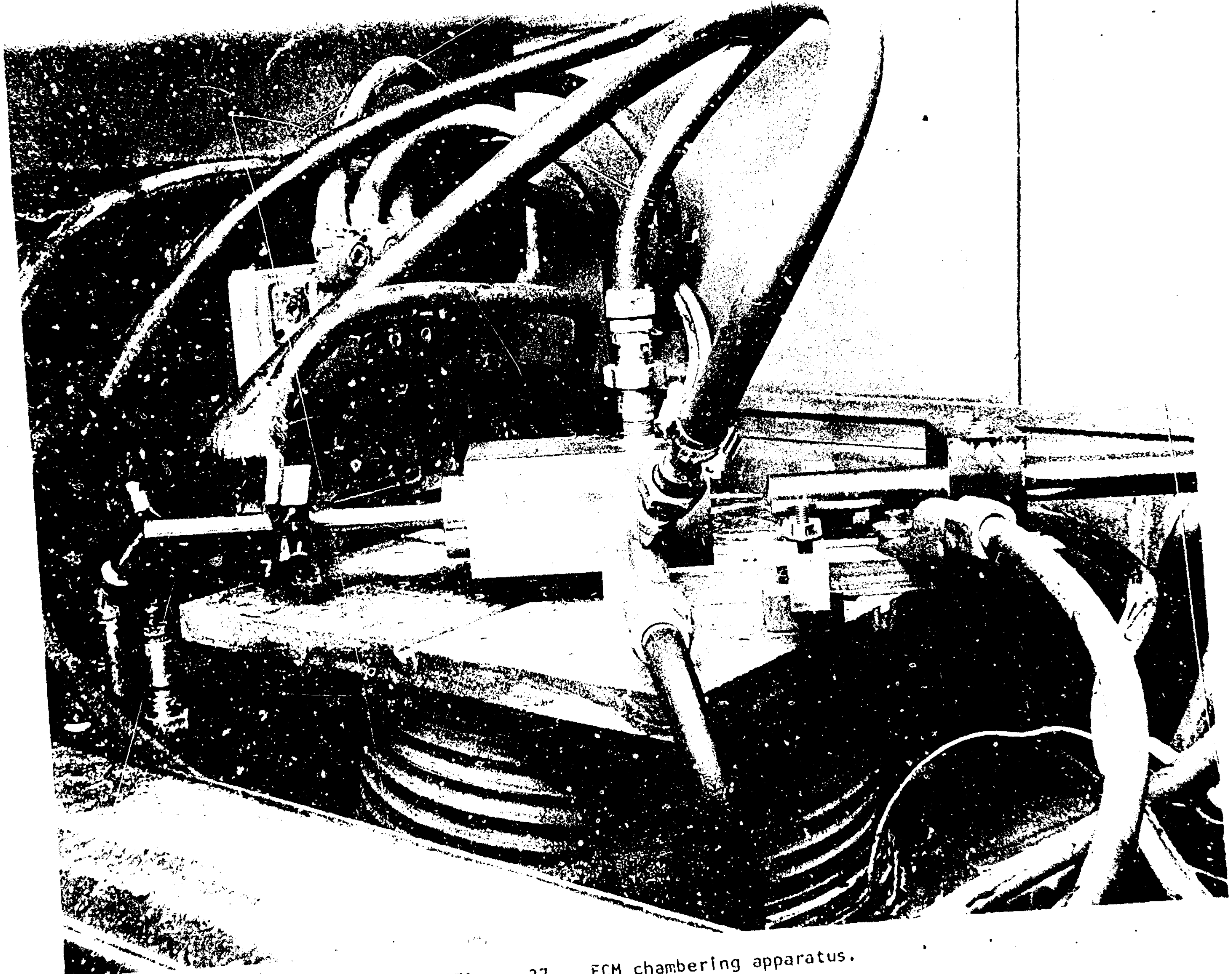


Figure 37. ECM chambering apparatus.

assembly, and locked in place with a bolt through the collet on the electrode. The barrel was forced along the guide surface and against the shoulder (1.0 inch into the assembly). The screws on the bar guide block were then tightened to secure the barrel to complete the preparation for chambering. Once the electrode has been located and locked in place it can be left permanently in this position because it has been located relative to the breech end of any blank fed into the barrel guide and against the shoulder.

The use of 1.195 ± 0.001 inch diameter blanks was selected for demonstration purposes to use either gun drilled or rifled blanks with a minimum amount of machining. For large volume finishing the barrel guide would require an inserted sleeve.

A limited number of chambering trials was performed to demonstrate the feasibility of this technique under the following conditions:

1. Electrolyte: NaCl (0.5 pound per gallon)

2. Electrolyte pressure: 175 psi

3. Electrolyte temperature: 100°F

4. Voltage: 20 volts

5. Current: 850 amps at start to 500 amps at finish.

Under these conditions finishing and polishing were performed at an average metal removal rate over the entire form of approximately 0.001 inch/sec. for Vasco M-A and 0.0005 inch/sec. for Inco 718.

The operating conditions were empirically selected based on past experience. The sodium chloride electrolyte was selected at the 0.5 pound/gallon concentration to reduce the metal removal rate to provide better control for the demonstration. Sodium chlorate would be a preferred electrolyte for this application because of its superior capability for reproducing the mandrel form and a fine surface finish. However, it is hazardous once it dries in contact with a combustible material. The superior behavior of sodium chlorate results from its relatively low throwing power which would necessitate a smaller cathode-anode gap. However, as the following results will show, the NaCl electrolyte, which required no special handling procedures, was more than adequate.

A cross section of a chamber produced in 16.5 seconds by ECM in a Vasco M-A gun drilled blank is shown in Figure 38. This chamber has a surface finish of 16 to 18 microinch AA which was produced from a reamed surface of 24 to 28 microinch AA. The narrow, bright circumferential band about 5/8 inch from the breech end is the remains of an intentional 0.003 inch overcut step in the chamber. The step appears to have been reduced to less than 0.0002

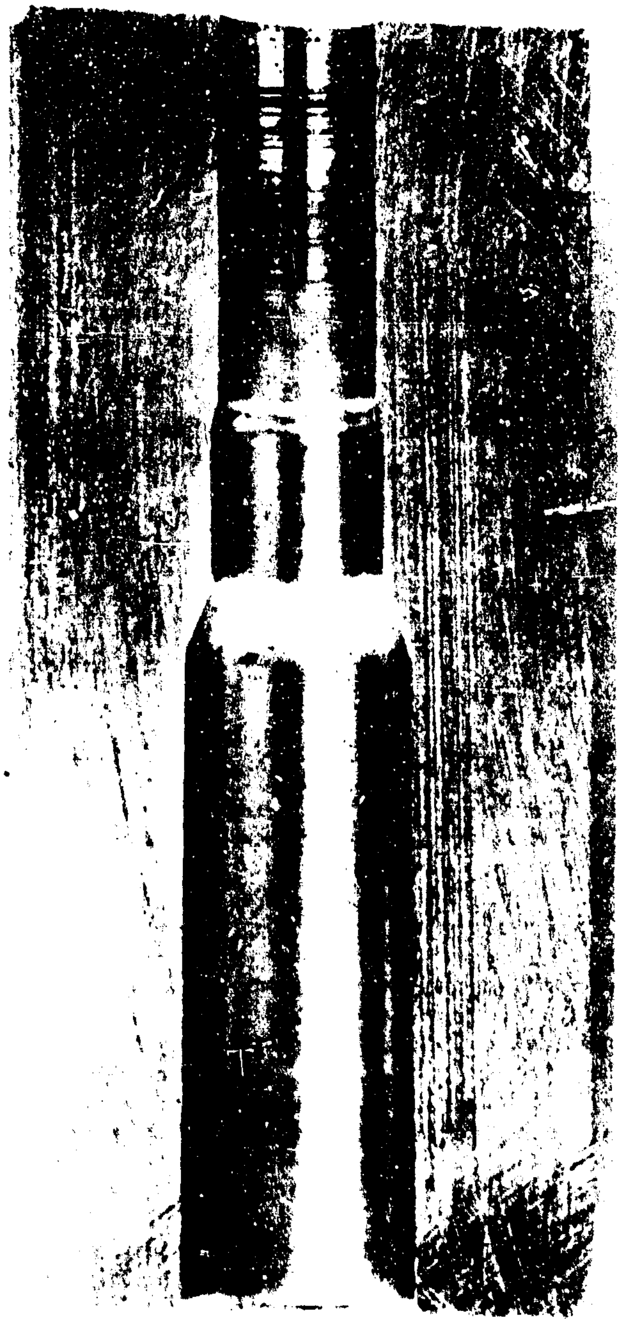


Figure 38. Cross section of chamber produced by ECM in Vasco M-A.

inch because it could not be detected with mechanical surface gauges. The black spots on this surface resulted from incomplete removal of the electrolyte after chambering. This problem was averted with subsequent trials as shown in Figure 39 for blank number M-5. This chamber was produced in an oversized blank to demonstrate taper into the bore. Spotting of this chamber was averted after chambering by immediate rinsing in tap water, methyl alcohol and spraying with rust inhibitor.

Figure 40 shows a chamber produced in Inco 718 in 27 seconds. No special rinsing precautions were necessary for this alloy, although the tap water rinsing to remove the salt is recommended. The original 0.004 inch step has been reduced to 0.0024 inches. Optical measurements on a cerrobend cast of the chamber produced by ECM in M-5 and shown in Figure 41 indicated that dimensional control on all flat and tapered surfaces can be maintained to within print dimensions as easily as with conventional chambering. However, ECM chambering is significantly faster and eliminates the need for subsequent polishing. ECM chambering with NaCl electrolyte rounds corners and enlarges some of the radii beyond print specifications. The taper of the bullet seat into the rifling was within the print specification, but could be improved by modification of the electrode nose. Trials with a stock removal of 0.008 inch produced specified radii; however, the other chamber dimensions were undersize with this electrode. Therefore, it was concluded that accurate chamber dimensions could be achieved with the NaCl electrolyte by using a total stock removal of 0.008 inch (maximum cathode-anode gap of 0.016 inch).

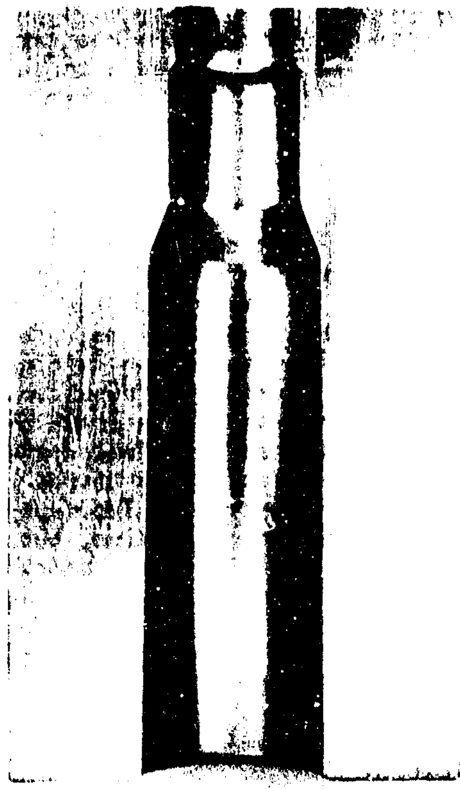
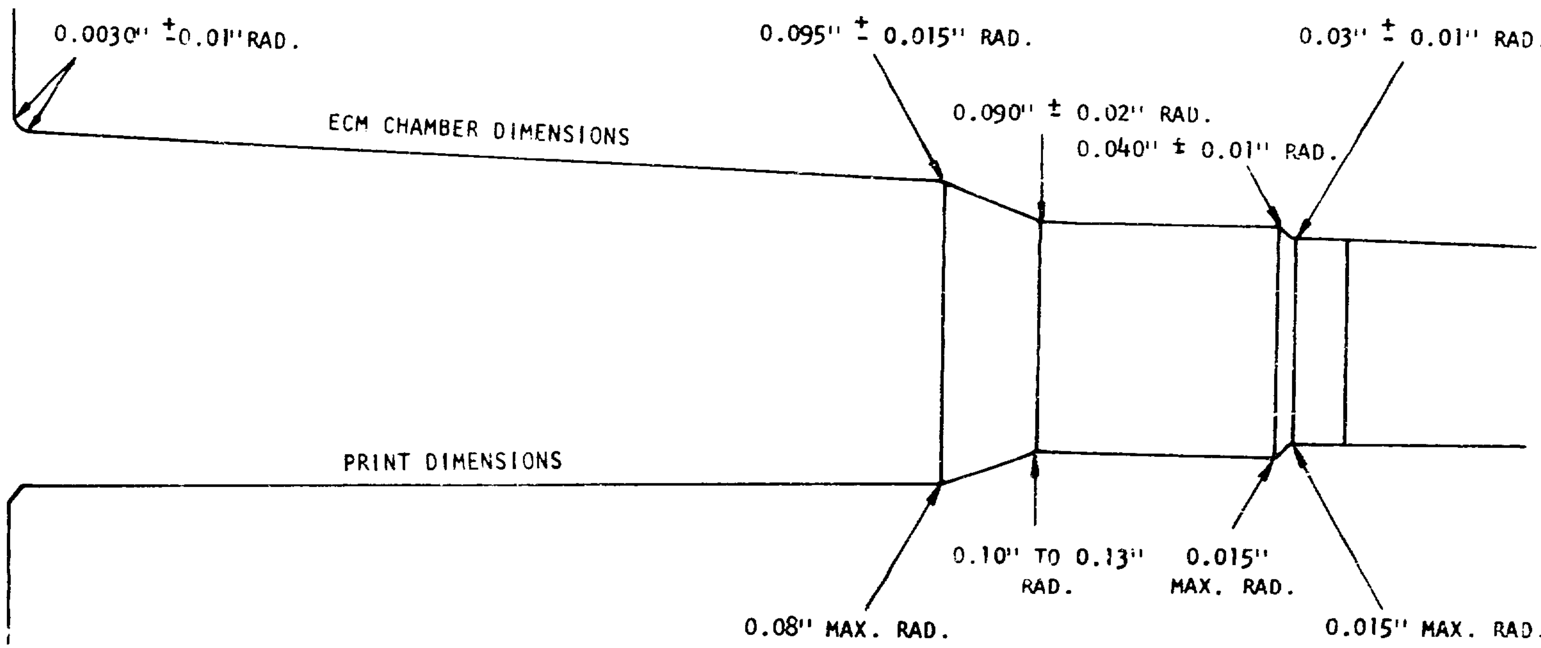


Figure 39. Cross section of chamber produced by ECM and adjacent rifled area in oversize blank number M-5.

Figure 40. Cross section of chamber produced in Inco 718 gun drilled blank S-3 showing remains of an originally machined 0.004-inch overcut step.



ALL PRINT AND ECM CHAMBER DIMENSIONS COINCIDE TO WITHIN ±0.0007 INCH EXCEPT AT RADII.

Figure 41. Comparison of print and ECM chamber dimensions for Vasco M-A blank number M-5 which was swaged oversize.

3.50 Barrel Finishing

Barrel finishing procedures were based on the factory routing used by TRW Inc. for manufacturing 384,000 Minigun barrels, U. S. Army Part No. 11701204, in 1965 and 1966. The procedures used on this project were established for tool room type finishing using, when practical, high production barrel finishing machines and additional procedures particularly amenable to superalloy processing. Major departures from the established procedures were necessitated by finishing rifled blanks which possessed a high level of residual stress. As a first step in finishing all blanks were stress relief annealed in vacuum for 1.5 hours at 900°F. The subsequent routing of the finished operations consisted of the following:

Operation No.	Operation
10	Receive barrel blank with rifled I.D. and smooth O.D., 1.200 + 0.000/-0.016 inch.
20	Inspect and straighten barrel blank bore using a production barrel straightener and shadow box.
30	Rough turn muzzle end on false centers.
40	Straighten barrel bore (see Oper. 20).
50	Qualify O.D. at 3 places with tracer lathe with barrel cam (template) and steady rest.
60	Rough turn O.D. to within 0.050 inch of muzzle end using soft jaws in the chuck.
70	Rough turn to within 0.050 inch of breech end, otherwise, similar to Operation 60.
80	Straighten bore per Operations 20 and 40.
90	Grind steady rest diameter with O.D. grinder with barrel located on false centers.
100	Finish machine muzzle end on tracer lathe using a template.
110	Finish machine breech end (similar to Operation 100).
120	Straighten bore with production bore straightener (see Operation 80).

Operation No.	Operation
130	Grind muzzle end at the four bearing surfaces to the finished diameter dimensions on an O.D. grinder with soft jaws in the chuck.
140	Grind breech end.
150	Mill 0.6975 flat on middle lug.
160	Mill radius and 53° angle on rear lug using Cincinnati Horizontal Mill and dividing heat with the part fitting through the dividing head.
170	Hand burr over all milled areas on burr bench.
180	Face and chamfer muzzle to length on a lathe.
190	Chamber barrel on lathe using 3 special tools.
200	Zyglo and Magnaflux inspect (as appropriate).
210	Super ream chamber (finish) on lathe with special tools.
220	Polish chamber on lathe with special tools.
230	Stamp barrel for identification (barrel blank number) with bench hand stamps.
240	Final inspection: 1. O. D. Dimensions, 2. Chamber, 3. Concentricity.

This routing has been established and all prints, check dimensions and tolerances established per normal production procedures. These operational prints and tables are available for review but will not be duplicated in this report because of their size and number. Although the routing was based on previous production fabrication of Cr-Mo-V barrels, the use of production equipment was not practical for the 24 barrel lot size and some of the previous production procedures are not applicable. Previous fabrication was performed on an alloy which is readily machinable and rifling was produced by broaching just before chambering.

The turning operations were performed using M-21 high speed steel and C-2 grade carbide tools on Inco 718 and C-2 and C-6 grades on Vasco M-A. The majority of the Inco 718 barrels were machined with high speed steel which outperformed carbide which failed predominantly by chipping very quickly during turning. This failure was attributed to the poor machinability of this alloy and the lack of rigidity which could be achieved in even a good barrel turning setup. The performances of C-2 and C-6 grades on Vasco M-A were virtually identical. Although C-2 appeared to wear more, C-6 was more susceptible to chipping. For both alloys, tool geometries recommended (1) for hardnesses in the range of R_c45 to 56 were used because they provided best results. The turning operations were performed with these tools and a medium duty water soluble oil under the following conditions:

	Max. Feed Rate	Speed	Max. Depth of Cut	Approximate Tool Life
Inco 718 R_c36	0.01 in/rev.	100 SFM	0.060 in.	40 in.
MA R_c36	0.015 in/rev.	250 SFM	0.080 in.	40 in.

For both MA and Inco 718 the maximum depths of cut could not always be used. These were used during the first three roughing passes, but were reduced to half on the succeeding. The final roughing pass was made as required to finish but a depth of cut always less than 0.2 times the maximum was used. The depth of cut during initial roughing was sufficient to overcome the effects of runout and, thereby,provided steady cutting conditions necessary for efficient use of carbide tools. However, the entire roughing operation was relatively aggressive as discovered during the subsequent straightening operation. In some cases for both alloys, roughing produced total indicated runouts from centers as large as 0.036 inch. The typical roughing sequences for Operations 30 and 50 (based on Operation 30) would consist of the following:

	Inco 718	Vasco M-A
Setup	1.6 min.	1.6 min.
Roughing*		
Passes 1, 2 and 3	8.9 min.	5.2 min.
Passes 4, 5 and 6	9.5 min.	5.7 min.
Tool change time/pc.	0.5 min.	0.5 min.
Pass 4	3.0 min.	1.8 min.
Tool Cost/pc.	$0.04	$0.12
Tool sharpening(time/pc.)	2.0 min.	2.0 min.
Discharge Time	0.5 min.	0.5 min.
Total	26.0 min.	17.0 min.

* Each pass includes cutting, return, measure and in-feed.

In general, Vasco M-A could be machined at approximately 2/3 the cost of Inco 718.

Turning, in general, was performed similar to the conditions discussed for Operations 30 and 50 when the stock diameter was appropriately considered. However, it should be recognized that tool room procedures were used and, therefore, the data are valid only for cost comparisons. The procedures in Operations 100, 110, 130 and 140 were generated to accommodate tool room practice, but could be combined as two abrasive machining operations. The use of abrasive machining would bring the cost down significantly for both alloys in production fabrication. Operations 100 and 110 are tracer turning operations to produce the cylindrical contours on the barrel and Operations 130 and 140 are grinding operations to finish the bearing surfaces to the final dimensions and surface finish. The combinations of Operations 100 and 130, and 110 and 140 into two operations could be performed on a multispindle crush-form grinder such as a Sheffield or a large single spindle machine. Using contemporary procedures and in-process gauging each of the two operations could be performed in as few as two feed cycles to produce the completely finished forms. Initial tooling setup costs for the cams or crusher rolls would be prohibitive for tool room production. However, their use in production fabrication could bring the costs for both Inco 718 and Vasco M-A down closer to the costs for performing these operations on conventional barrel materials.

Chambering is a very critical operation with superalloys because of the high probability for tool breakage if precautions are not taken. For these reasons, conventional chamber reaming of superalloy barrels is time consuming and expensive. Therefore, ECM chambering should be a significant development. Production chambering for conventional materials utilizes several sequences involving core drilling and gun reaming in an automated machine. The chamber form is generated in length and diameter to avoid large tool forces arising from localized tool breakdown from excessive cutting on the shoulder forms. Gun reaming is necessary for production fabrication to remove chips, to provide a plentiful supply of cutting fluid and to provide consistent tool performance. During tool room chambering some of the steps can be averted because the machinist can sense problems which the automated machine cannot. Therefore, the total chambering sequence used for the barrels contains at least one and probably as many as three operations less than would be used in actual production. The total chambering sequence consisted of the following:

1. Rough pilot ream 0.432 inch diameter hole and neck taper 0.015 inch from finished dimensions using an M-42 high speed steel four-fluted reamer.

2. Step core drill (0.457 inch/0.447 inch) up to previously roughed neck taper using an M-42 high speed steel core drill.

3. Rough taper ream to within 0.008 inch of finished size on chamber body and neck and to within 0.012 inch in the throat. This step was performed using a full form piloted gun reamer with inserted and brazed C-2 grade carbide blades over the entire form.

4. Semi-finish ream entire chamber form to within 0.003 inch using a full, piloted form gun reamer with brazed carbide inserts.

5. Finish ream entire chamber form using a full form piloted M-42 reamer.

6. Polish entire chamber using crush formed felt cylinders charged with abrasive.

In steps 1, 2 and 5 coolant is fed in along the flutes of the tools at 50 psi pressure. These operations were performed by feeding the tool in three increments of approximately 0.75 inch, 0.5 inch and to finish. After each feed increment the tool was brushed with nylon bristles to remove the chips and then fed in the next increment. Steps 3 and 4 were performed with gun reamers with high pressure cutting fluid injected through the tool and out of ports at the base of the pilot to drive the chips out of the breech. This step was performed in one feeding operation.

The surface finish of the chamber after step 5, the finish reaming operation, was in the range of 25-35 microinch AA which was easily improved to below 32 by polishing.

ECM chambering was performed after step 3. However, steps 2 and 3 would have been performed with less stock removal. The ECM procedure which was developed required less total time for setup and stock removal than any one of the six mechanical stock removal operations and resulted in the elimination of steps 4, 5 and 6. Because the ECM procedure is amenable to mass production, it is anticipated that similar results would be obtained in production fabrication.

4.0 EVALUATION OF FABRICATION PROCEDURES

The evaluation of the fabrication procedures investigated during this program is based on the measured performance transformed into time per piece and tool cost. No factor is used for defect or reject probability; however, this particular problem was discussed in the section on results and is only briefly reviewed with each evaluation. The following evaluations are concerned primarily with tube fabrication involving gun drilling, ECM stem drilling, hot piercing and extrusion, and filled billet extrusion, and how these procedures best fit into a total fabrication sequence.

4.10 Gun Drilling

Stock for gun drilling can be purchased as conventional centerless ground bar. As was shown in Tables I, II, and XII heat treatments for either steel or Inco 718 may cause distortion of the bar which, in general, will not significantly affect swaging performance after gun drilling. Therefore, the major concern in gun drilling is how will the final barrel properties be achieved, since heat treatments could be used before or after gun drilling.

Because Inco 718 can be obtained in the hardness range of approximately Rb 92 to Rc 36 by solutioning followed by air cooling (very rapid air cooling of thin sections will produce lowest hardness vlaues), it should be drilled in this condition where optimum gun drilling results were obtained. This procedure would also avert problems with surface contamination and chromium depletion at the high solutioning temperatures. Subsequent aging at 1350°F or lower even in an air furnace for as long as 12 hours produced a very light green discoloration of the surface apparently from chromium oxide. Aging after gun drilling could be performed with negligible distortion and without stringent atmosphere control. Therefore, the optimum condition for drilling Inco 718 appears to be the as-solution treated and rapidly air cooled (AMS 5662) treatment at a feed rate of 0.56 inch/minute and speed of 100 SFM producing a wear land of 0.010 inch or less.

Vasco M-A cannot be drilled in the austenitized and quenched condition which produces near maximum hardness in this alloy. It could be drilled in the as hot-worked condition (approximately Rb 95) and either heat treated with special atmosphere protection or conventionally with a subsequent bore conditioning operation. Both of these procedures would involve additional operations which may not be necessary. Because of the excellent gun drilling results obtained at Rc 36 with this alloy and the similarity of these results with low alloy steels, the most economical procedure for gun drilling this alloy in the hardness range up to about Rc 45 appears to be in the as-tempered condition. The results in Table III indicated that this drilling can be performed at 200 SFM with a feed of 1.8 inch/minute to provide a tool life anticipated to be 160 inches for a 0.010 inch wear land.

An analysis of the gun drilling operation is developed in terms of productivity per manhour, productivity per machine-hour, and tool cost per piece. This analysis is based on the use of a single spindle machine which automatically retracts, a common feature even on tool room machines. Tool cost per piece is based on the original purchase price in lots of 2 ($45/drill) and a 0.010 inch removal per sharpening or 100 sharpenings per drill. These considerations provide the following:

Initial setup cost - negligible.

	Man - Minutes		Machine - Minutes	
Operational Step	Inco 718	Vasco M-A	Inco 718	Vasco M-A
1. Gun Drilling				
Setup time/piece	1.00	1.00	1.00	1.00
Drilling time/piece	-	-	41.00	12.80
Retraction (2 in/sec)			.20	.20
Discharge time/piece	1.00	1.00	1.00	1.00
Total gun drilling time/piece	2.00	2.00	43.20	15.00

2. Sharpening					
Time/piece		3.00	0.42	3.0	0.42
Total Time/Piece:		5.00	2.42	46.2	15.42
Tool Cost/Piece:	Inco 718	$0.45		Vasco M-A	$.064

	1 Man-Hour		1 Machine-Hour	
	Inco 718	Vasco M-A	Inco 718	Vasco M-A
Productivity (barrels/hour)	12	24.9	1.30	3.89
Cost (dollars/hour)	$5.40	$1.59		

With 100 percent efficiency and immediate access to a machine after it retracted, one man in principle would be operating 23 machines drilling Inco 718 and 13 machines drilling Vasco M-A. Obviously, these results for the assumption of single spindle machines are impractical as well as absurd. In actual production fabrication of barrels multispindle machines are used. Using 6 spindle gun drilling machines, the developed productivity and cost figures with the assumption of 80 percent efficiency would be a practical estimate for this tube fabrication procedure. Therefore, the approximate costs per gun tube for this production procedure would be about $2 to $3 for Inco 718 and $1 to $1.50 for Vasco M-A. These figures were based on $10 labor plus overhead per manhour and $3 per machine-hour.

4.20 ECM Stem Drilling

ECM drilling can be performed on any conducting material independent of its hardness. However, the actual microstructural condition of the alloy can affect the drilling performance through a dependence of surface finish on the microstructural constituents, soluble concentration of workpiece material in the electrolyte, and concentration of sludge or solid particles. Based on the valences and densities of iron and nickel and Faraday's law, it was assumed that Inco 718 and Vasco M-A would ECM at approximately the same rate to within 10 percent. However, for both drilling and chambering, the metal removal rate of Inco 718 appeared to be approximately 1/2 that of Vasco M-A. This difference of rates was measured directly during chambering and was deduced during drilling by the oversized hole obtained with Vasco M-A using the ECM parameters developed for Inco 718. Therefore, it is assumed for this evaluation of ECM drilling that the feed rate for Inco 718 is 0.027 inch/minute as measured and 0.05 inch/minute for M-A as predicted. Based on these rates, the following evaluation was performed assuming the use of centerless ground bar stock:

initial setup costs: approximately $2000 for the electrode, electrode guiding fixtures, grips and preliminary machine-fixture evaluations.

Operational Step	Man-Hours Inco 718	Man-Hours Vasco M-A	Machine-Hours Inco 718	Machine-Hours Vasco M-A
1. Setup (time/piece)	0.067 (4 min.)	0.067	0.067	0.067
2. Drilling (time/piece)	-	-	14.33	7.75
3. Discharge (time/piece) (total)	0.10	0.10	0.083	0.083
a. Retraction of electrode				
b. Removal of piece from grips				
c. Rinsing				
d. Coating with inhibitor				
4. Ream Exit End	0.017	0.017	-	-
Total Time per Piece	0.184	0.184	14.480	7.900

The electrolyte consumption, which will depend on settling of solids, was assumed to be 1 gallon per barrel. With an electrolyte of 15 v/o sulfuric acid (lot price $0.21/pound or $3.20/gallon for C.P. H_2SO_4) this cost would be $0.48 per barrel. The cost of electrical power at a current density of 1000 amps/in.^{2} or 80 amperes at 8 volts is relatively insignificant and comparable to the cost of operation of a one horsepower motor.

This evaluation of ECM drilling shows that a large capital investment would be required to fabricate tubes at rates required for production. A machine with motors, pumps, electrolyte settling reservoir and necessary electronic controls would cost in the range of 15 to 25 thousand dollars when purchased in large numbers. Furthermore, indirect labor costs in terms of general surveillance and calibration could be in excess of 0.3 hours per barrel

Tool wear should be negligible during ECM drilling. However, tool wear could be high if the electronic controls malfunction and if alignment of the electrode were difficult to maintain. Under these conditions arcing could occur which would affect the bore surface similar to the effect of an EDM discharge.

The use of ECM hole drilling of gun tubes is not recommended for production fabrication of superalloy barrels unless gun drilling cannot be performed. The major basis for this deduction is the low feed rates attainable with this technique which would necessitate a large capital investment necessary to meet typical production schedules for military weapons.

4.30 Hot Piercing and Extrusion

Hot piercing and extrusion can be performed on most superalloys using the following procedures:

1. Gun drilling a billet with a centrally located hole to closely fit the mandrel;

2. Heating of the billet to the appropriate extrusion temperature;

3. Extruding the tube over a mandrel;

4. Reconditioning and replacement of the die and mandrel for the next billet;

5. Tube straightening;

6. Cutting of tube to the desired length;

7. Heat treatment of the tube;

8. Grinding of the O.D. on centers;

9. Bore conditioning, a removal of 0.004 inch minimum thickness from the bore surface;

In this outline of procedures for tube fabrication by hot piercing and extrusion, it is assumed that a bore diameter of 0.320 inch can be achieved, which is marginal with current materials used for mandrels. A larger diameter bore would require more reduction by swaging. It is also assumed that tubing of this diameter would be obtained from 6 inch diameter billets 10 inches long with an 80 percent yield, which is very good but similar to what was obtained in this program for 3 inch diameter billets. For these conditions the following times and costs are obtained for Inco 718.

Initial setup cost: approximately $1500 for guide tooling

		Costs and Hours per Gun Tube		
		Costs	Man-Hours	Machine-Hours
1.	Billet preparation	$0.25	-	0.062
2.	Mandrel cost	$1.80	0.067	0.248
	a. 1 mandrel/3 billets @$40/mandrel			
	b. Reconditioning of mandrel ($/tube)			
3.	Die Cost	$0.85	0.067	0.062
	a. 1 die/10 billets @$60/die			
	b. Reconditioning of die ($/tube)			
4.	Extrusion with automatic heating furnace		0.052	0.407
	a. Setup			
	b. Extrude			
	c. Remove old tooling			
5.	Straighten		0.0062	0.050
6.	Cut to length and face		0.02	0.02
7.	Solution heat treat (100 per batch)		0.003	0.015
8	Prepare bore (ECM bore)		0.08	0.08
9.	Rough grind on centers		0.20	0.20
10.	Scrap ($3/lb.)	$4.80		
	Total	$7.70	0.4952	1.144

The costs and times developed for hot piercing and extruding Inco 718 are very optimistic. The evaluation is based on a quasi-line type of operation and the assumption of a relatively large extrusion press dedicated to this operation which would require at least two men for operation, and an automatic heating furnace. It is assumed that only two men would be required for extrusion. Therefore, based on this evaluation hot pierced and extruded tubes of Inco 718 could not be produced for less than $12.00 per piece or approximately 3 to 4 times the price of gun drilling. It should be noted that the yield from this process produces a significant additional material cost which cannot be reclaimed.

4.40 Filled Billet Extrusion

The procedure established for the filled billet extrusion of the cobalt-base superalloy powder consisted of the following steps:

1. Fabricate can and core components;
2. Sandblast and degrease can;
3. Weld one end of can assembly vacuum tight under an inert gas;
4. Load accurate weight of powder charge (measured density) into can;
5. Assemble can and electron beam weld complete assembly under vacuum;
6. Heat to temperature and extrude;
7. Repair and/or replace die as required;
8. Straighten extruded tube;
9. Cut to length;
10. Heat treat as required for subsequent machining and swaging;
11. Straighten heat treated tube to 0.010 inch/foot;
12. Rough grind or turn O.D. on centers to remove the can and to achieve concentricity of the O.D. and centerline;
13. Prepare inner diameter as required.

The preparation of the tube bore can be achieved by chemical, electrochemical or mechanical techniques. Chemical leeching of a filled core is time consuming and, in some cases, may not be competitive in terms of time and cost with gun drilling. Therefore, in the cost analysis, the use of gun drilling is assumed to define an upper limit on cost for core removal.

The evaluation is performed with the additional assumptions of extruding 8 tubes from a 6-inch diameter billet with a yield of 75 percent, which is better than was observed. With these assumptions the operational times and costs per gun tube are determined as follows:

Operational Step	Material Costs	Man-hrs/barrel	Machine-hrs/barrel
Billet Fabrication			
1. Fabricate case and core		0.084	0.084
2. Clean, assemble, fill and weld assembly		0.050	0.250
3. Cost($/barrel)-mild steel can	3.45		
Extrusion with Automatic Heating Furnace			
1. Extrude		0.013	0.067
2. Replace die and follower block		0.013	0.020
Straighten		0.007	0.050
Cut to length and face		0.020	0.020
Heat treat		0.001	0.003
Straighten		0.010	0.010
Rough grind(decan)		0.200	0.200
Prepare bore		0.080	0.080
Cost of scrap/barrel (Material cost $7/lb.)	14.00		
Total (per barrel)	$17.45	0.478 hrs.	0.784 hrs.

These results for filled billet extrusion of powder indicated that a tube cannot be produced for less than about $23. As was the case with hot piercing and extrusion, the costs for the filled billet technique are significantly affected by yield. For this technique the raw material costs are high and, therefore, the costs per pound of scrap will be affected accordingly. The costs developed for the filled billet technique are conservative to the same extent as the hot-piercing and extrusion costs. However, it should be recognized that the filled billet procedure can be used with two types of starting material: 1) solid bar and 2) powder. When powder is used the filled billet procedure becomes more competitive because the powder must be consolidated. In general, alloy powders must be worked to achieve full density necessary for strength and toughness. For this reason the filled billet technique could be used as an improved consolidation procedure to achieve a cost reduction. However, the cost reduction wold not be more than 10 or 15 percent less than the cost for the conventional canned extrusion consolidation procedure unless the barrel material was exceptionally difficult to gun drill.

4.50 Summary of Process Evaluations for Tube Fabrication

Gun drilling has been found to be the most economical process for producing tubes of Inco 718 and Vasco M-A. It is anticipated that this observation will also be applicable to all high strength steels and most superalloys in a metallurgical condition directly amenable to subsequent barrel fabrication or a condition which will fit into an overall fabrication scheme utilizing an intermediate heat treatment.

The toughness requirements of small caliber weapons make it doubtful that either high strength steels or superalloys will be fabricated into barrels at hardness levels in excess of Rc 45. Barrels could be economically fabricated at or below this level by gun drilling and swaging by using high strength steel centerless ground bar stock tempered to this hardness initially and by using centerless ground superalloy bar stock in the solution annealed and rapidly air cooled (hardness of Rc 36 or less) condition initially with subsequent low temperature aging treatments as an intermediate or final fabrication step. These latter treatments could be performed without stringent furnace atmosphere control and, if the bore is to be electropolished, aging could be performed in air.

The other processes (ECM stem drilling, hot piercing and extrusion, and filled billet extrusion) were found to be less economical than gun drilling based on the results for Inco 718 and Vasco M-A for fabrication of homogeneous barrels. These findings were extrapolated to other superalloys and high strength steels based on their gun drilling and heat treatment responses which are similar to Inco 718 and MA. The major shortcoming of ECM stem drilling is feed rate which would necessitate a large capital investment in equipment to meet typical barrel production schedules. Hot piercing and filled billet extrusion suffered from the requirement of many secondary tube conditioning processes which added to the tube cost. If a future requirement necessitated the use of alloy powders, this consolidation could be economically performed by filled billet extrusion incorporating a central core of mild steel extruded smaller than the tube diameter. After straightening, this core could be removed by gun drilling to provide an accurate hole and to eliminate further necessity for bore conditioning.

5.0 CONCLUSIONS

A program was performed to develop advanced fabrication techniques for 7.62 mm superalloy gun barrels. The techniques which were investigated for tube fabrication included gun drilling, ECM stem drilling, hot piercing and extrusion, and filled billet extrusion. It had been predetermined from past experience that precision rotary swaging was one of the most economical procedures to produce rifling in U. S. Army part No. F110701204. The swaging process was investigated to determine the feasibility for producing sufficiently large reductions in Inconel 718, Vasco M-A and the cobalt base alloy to achieve additional economic benefits from reduced tube fabrication costs, and combined rifling and chambering. Barrel finishing procedures were evaluated using tool room practices to determine finishing costs and problems, and an ECM chambering procedure was developed and demonstrated.

Tube fabrication by gun drilling was found to be most economical for Inco 718 and Vasco M-A at hardness levels to Rc 45. This drilling was performed with special tools designed for use on these alloys. Although the other procedures were found to be less economical than gun drilling for producing Inco 718 and Vasco M-A homogeneous barrels, they may be useful for other alloys or applications such as lined barrels and barrels fabricated from powder.

Precision rotary swaging was found to produce rifling with a precision of better than 0.0001 inch on the grooves. In general, less precision was achieved in producing the lands indicating that production fabrication procedures should utilize large reductions to insure prolonged contact of the bore and mandrel particularly along the grooves. Both Inco 718 and Vasco M-A at hardnesses of nominally Rc 36 would withstand reductions in excess of the amount required for simultaneous rifling and chambering. However, the cobalt base alloy tubes cracked during swaging to the minimum reduction required for rifling.

ECM chambering was demonstrated for Inco 718 and Vasco M-A and was found to eliminate two reaming operations and polishing previously used in production fabrication of these barrels from Cr-Mo-V steel. This process appears readily amenable to production fabrication to achieve a cost reduction even on conventional barrels and should be more desirable for fabrication of barrels from advanced materials.